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ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 116

TEMPERATURE CONTROL IN OUTDOOR EXPERIMENTAL PONDS

by
H. Stefan, E. Silberman,
P. Vaidyaraman, and W. Geiger

With Contributions and an Appendix by
E. R. G. Eckert, R. Goldstein, E. Sparrow, and R. Kolar
of the Heat Transfer Laboratory of the
Mechanical Engineering Department, University of Minnesota

Prepared for
NATIONAL WATER QUALITY LABORATORY
Federal Water Quality Administration
Duluth, Minnesota

December 1970
Minneapolis, Minnesota

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University of Minnesota
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TEMPERATURE CONTROL IN OUTDOOR EXPERIMENTAL PONDS

A. INTRODUCTION

The National Water Quality Laboratory (NWQL) of the Federal Water Quality Administration located at Duluth, Minnesota, proposed to build and operate a number of outdoor experimental ponds for the study of aquatic life under the effects of various controlled water temperatures. The ponds were to be located near the electric power generating plant presently under construction near Monticello, Minnesota, on the Mississippi River and owned by Northern States Power Company (NSP). Waste heat from the power plant and local ground water supplies were to be available for establishing the controlled temperature regimes in the ponds.

The purpose of the study reported upon herein was to determine the feasibility of maintaining certain specified temperature regimes in the proposed ponds. This was to be done by considering the available heating and cooling capacity and the environmental conditions prevailing at the selected site and making design calculations for the major elements of the system required to maintain those temperature regimes. The NWQL suggested certain basic specifications to control the study. These were as follows:

> The ponds should represent natural conditions insofar as is compatible with maintaining the desired experimental temperature regimes. Eight ponds should be considered in the first stage, operating in pairs at four different temperature regimes (each regime would be duplicated). Ultimately, as many as 32 ponds might be built. In mid-summer a maximum temperature of 30°C and a minimum of 15°C (59°F) are desired. The flow rate into and out of each pond should be the same at all times so as to produce equal effects on the biota in the several ponds. The total pumping capacity for heating water would be 2800 gallons per minute, and it is anticipated that wells would provide 40 to 80 gallons per minute of cooling water. Each pond would have a surface area of one quarter of an acre. The maximum depth would be 8 ft, and there would be vertical walls on the two ends; the two sides would have 1:6 slopes. (The geometry proposed by the NWQL is shown in an isometric sketch in Fig. A-1.)

The ponds would be constructed with Gunite two to three inches thick; the existing sand would be stabilized to provide a base for the Gunite, and natural substrate would cover the Gunite. Ponds would be constructed so that two could be joined if so desired at a later date. Each pond would have an overflow. Piping for recirculating or adding water to ponds must provide for minimum toxic substances; the use of stainless steel or plastic materials is strongly suggested.

The first goal of this study was to determine the limits of feasible temperature control in experimental ponds of the kind suggested by the NWQL. The next goal was to devise heating and cooling systems to maintain four different pond temperature regimes within those limits while minimizing temperature differences within a single pond. (Small temperature differentials are necessary, however, and would be permitted to provide the necessary heat fluxes for the heating or cooling of the pond; ±3 deg F would be tolerated for this purpose.) Lastly, it was necessary to devise a method by which pond temperature control could be accomplished.

Unfortunately, it was not possible to reach the goals of this study in a straightforward manner. The feasible range of pond temperatures depends both on the capability for transferring heat to or from the pond water from the hot and cold water supplies and on the environmental heating or cooling of the ponds. Since heat transfer capability is not unlimited and depends on pond temperature, it is a matter of cut-and-try to determine that maximum (or minimum) pond temperature which can just be supported by the available capability under the given environmental conditions. The quantitative evaluation can be started with assumed pond water temperatures. Based on these, the heat transfer from or to the sources of hot or cold water and to or from the atmosphere can be evaluated. If these are not equal, new pond water operating temperatures have to be assumed and the design repeated until satisfactory agreement is reached.

Thus, before proceeding with the study, two preliminary subjects had to be explored. These were the mechanics of heat transfer to and from a body of water and the establishment of the environmental hydrological and meteorological conditions at the pond site. These topics influence not only the heat transfer to and from the ponds, but also the transfer to and from the Mississippi River, whose temperature ultimately determines the temperature of the available heating water. These subjects are discussed in detail in parts B and C, following, while the detailed calculations for the proposed ponds are carried out in the subsequent parts.

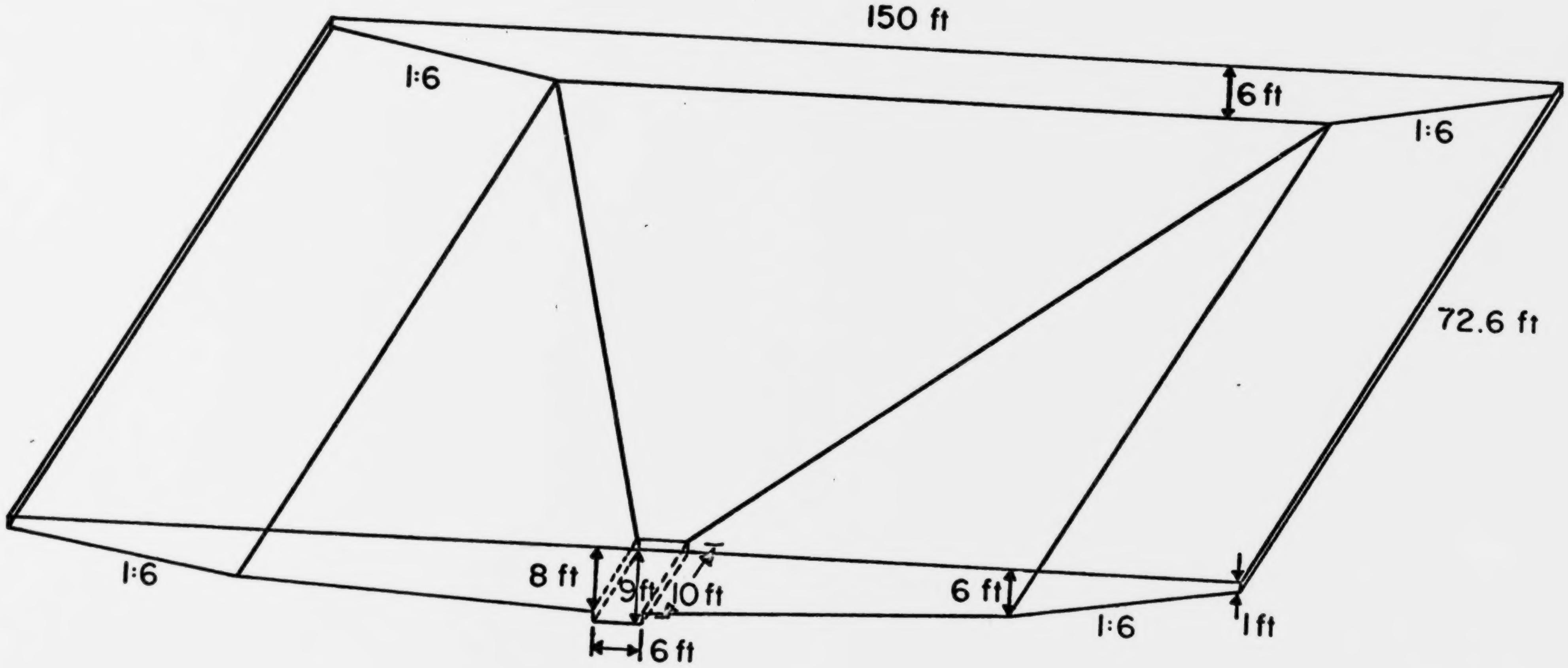

150 ft
1:6
6 ft
1:6
72.6 ft
8 ft
9 ft
10 ft
6 ft
1 ft
1:6
1:6
6 ft

Fig. A-1 - Isometric Sketch of an Outdoor Experimental Pond

B. HEAT TRANSFER THROUGH A POND SURFACE

The amount of heat addition or withdrawal required to maintain a specified water temperature in a pond can be determined using various empirical or semi-empirical relationships which have been developed in connection with the design of cooling ponds or during evaporation studies. Addition or loss of heat will occur mainly through the water surface and is associated with the following natural phenomena: solar radiation; backradiation; conduction, convection, and evaporation to the atmosphere; and precipitation. There are also other sources of heat addition or heat loss along the bottom of the pond and in the pond. These are associated with seepage, conduction through the soil, and metabolism of living organisms. These last three items are of minor importance, and can be ignored, as is shown later. Figure B-1 shows the types of heat input and output of the pond schematically.

Practical predictions of heat exchange rates at a water surface are generally based on semi-empirical relationships. The basic form of such relationships is outlined in Ref. [1]*, which also contains a bibliography on the subject. The theoretical background of most relationships has been summarized in Ref. [2], which was largely used in the present study.

The net heat flux H_n through a water surface is the algebraic sum of net solar radiation H_s, net atmospheric radiation H_a, backradiation H_{br}, conduction and convection H_c, and evaporation or condensation H_e, heat advection by precipitation H_p, and heat advection by flow into or out of the pond H_{ad}.

$$H_n = H_s + H_a + H_{br} + H_c + H_e + H_p + H_{ad} \tag{B-1}$$

The first six terms on the right-hand side of Eq. (B-1) are the result of specific meteorological conditions in combination with a given pond water temperature. The last term represents heat addition or withdrawal by water flowing into or out of the pond as will be necessary, for example, to make up for evaporation losses or to heat or cool the pond. The evaporation term H_e, the precipitation term H_p, and the advection term H_{ad} are thus associated with a mass flux into or out of the pond. A steady pond water temperature in a well mixed pond will be maintained if the net heat flow into and out of the pond is zero; i.e.,

---

*Numbers in brackets refer to the list of references on pages 62 and 63.

$$H_n = 0 \tag{B-2}$$

This necessary condition for constant (time-independent) pond water temperature in a well mixed pond is rarely satisfied. The pond water temperature at which Eq. (B-2) is valid is called the equilibrium temperature E. [If the pond is not well mixed, Eq. (B-2) does not guarantee time-independent temperatures. Internal heat flows caused by temperature gradients in the water will change water temperatures with time.] At water temperatures different from E the right-hand side of Eq. (B-1) does not add up to zero. If a water temperature different from E is to be maintained, heat has to be added or withdrawn at a rate equal to the value of H_n for the desired pond water temperature. The design of an artificial heat exchanger therefore requires that the net heat flux H_n into and out of the pond be known.

Each of the terms on the right-hand side of Eq. (B-1) varies with time. The magnitude of solar radiation H_s can be obtained from recorded measurements, while the other values can be computed from the following relationships [2]:

$$H_a = \epsilon_a \sigma (T_a + \Delta)^4 \tag{B-3}$$

$$H_{br} = \epsilon_w \sigma (T_s + \Delta)^4 \tag{B-4}$$

where ϵ_a and ϵ_w are the emissivities of air and water, respectively, and $(T_a + \Delta)$ and $(T_s + \Delta)$ are the absolute temperatures of air and water respectively.

$$H_e = f(U,\psi)(e_s - e_a) \tag{B-5}$$

$$H_c = c_1\, f(U,\psi)(T_s - T_a) \tag{B-6}$$

where e_s is the saturation vapor pressure of water at the water surface temperature T_s and e_a is the actual water vapor pressure in the air (saturation vapor pressure at the dew point temperature of the ambient air). The actual vapor pressure of the atmosphere at a given temperature T_a can be determined from the relative humidity r. The function $f(U,\psi)$

depends on wind speed U at a specified distance above the water surface and on dynamic variables ψ which account for the motion in the water and air boundary layers near the water surface; c_1 is a numerical constant in the Bowen Ratio.*

The heat added by precipitation, H_p, can be estimated from precipitation records:

$$H_{p,rain} = I\rho c_p(T_p - T_s) \tag{B-7}$$

where I is the rainfall intensity, ρ is the density of water, c_p is the specific heat of water, T_p is the temperature of the precipitation, and T_s is the pond water temperature. In case of precipitation in the form of snowfall the above equation must be replaced by

$$H_{p,snow} = I\rho[c_{p,s}(T_p - T_f) + c_p(T_f - T_s) - L_f] \tag{B-8}$$

where T_f is the freezing temperature, $c_{p,s}$ is the specific heat of ice or snow, and L_f is the latent heat of fusion. In Eq. (B-8) I is the water equivalent of the snowfall intensity.

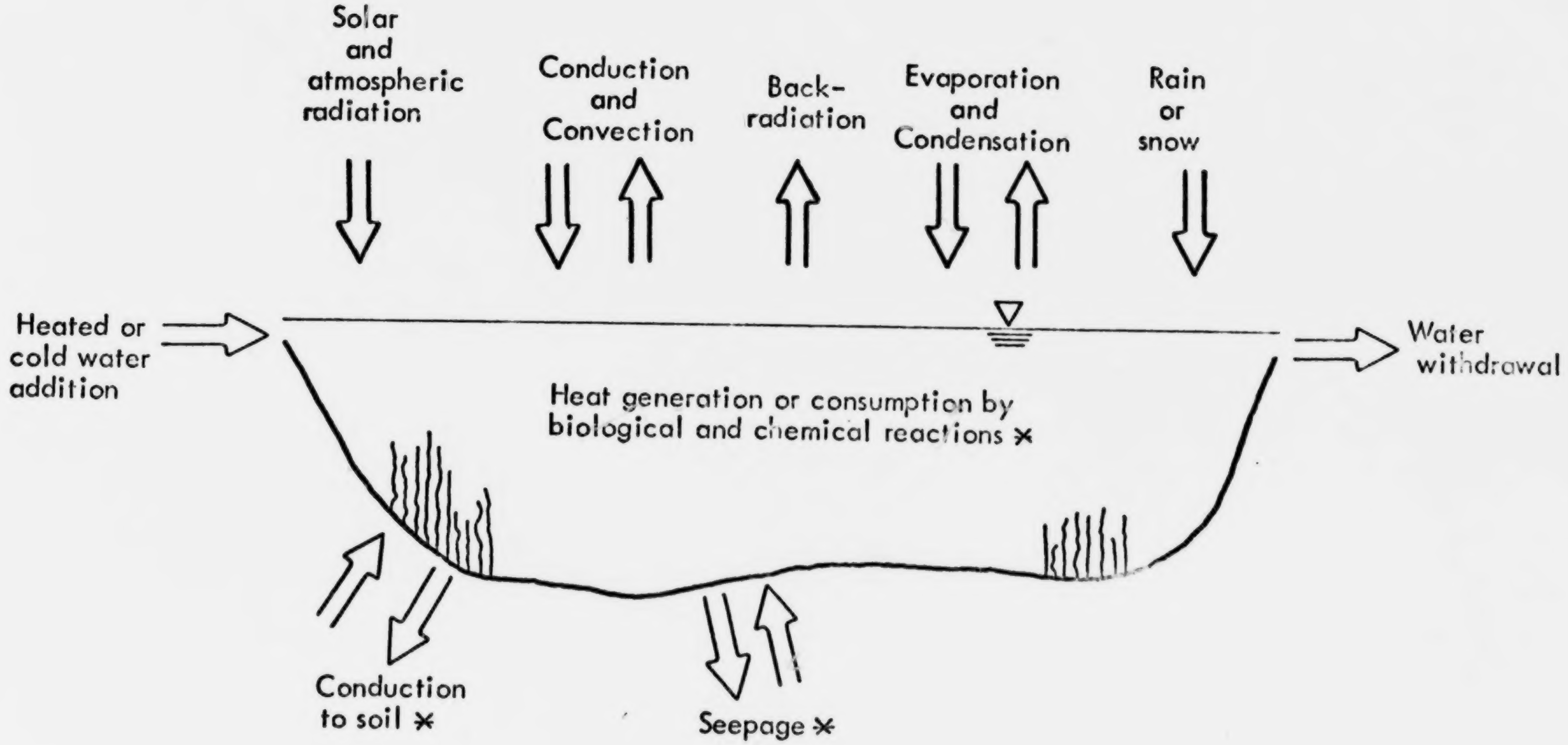
The advection term H_{ad} is a function of the flow rate Q and the temperature difference $(T_{ad} - T_s)$, where T_s is the pond water temperature and T_{ad} is the temperature of the added or withdrawn water.

$$H_{ad} = \rho c_p Q_{ad}(T_{ad} - T_s) \tag{B-9}$$

Examination of the afore-mentioned relationships shows that at least seven meteorological and hydrological parameters influence the heat loss through the water surface: net solar radiation received H_s, air temperature T_a, wind speed U, pond water temperature T_s, relative humidity r, and intensity I and temperature of precipitation T_p. The values of these parameters for the present study were obtained from various sources and are presented in part C, following. The actual numerical computation of heat loss values is carried out in part D.

---

*Use of the Bowen ratio is a means of eliminating conductive and convective heat transfer from the heat budget equation. Since conduction and convection depend essentially on the same parameters as evaporative heat transfer, it is reasoned that the ratio of these terms to the evaporative term should be a constant, called c_1 in Eq. (B-6). The constancy is open to considerable dispute, as is pointed out in Ref. [8].


Solar
and
atmospheric
radiation
Conduction
and
Convection
Back-
radiation
Evaporation
and
Condensation
Rain
or
snow
Heated or
cold water
addition
Water
withdrawal
Heat generation or consumption by
biological and chemical reactions *
Conduction
to soil *
Seepage *

* Considered as negligible for purpose of this study

Fig. B-1 - Elements of Heat Budget for a Natural Pond

C. HYDROLOGICAL AND METEOROLOGICAL DATA

1. Temperature of Water Supply

1.1 Mississippi River Water Temperatures at Monticello, Minnesota

There is no temperature recording station on the Mississippi River at Monticello, Minnesota. Therefore records of temperatures obtained at other locations shown in Fig. C-1--mostly downstream from Monticello--have been assembled and analyzed.

a) The Hydrologic Investigations Atlas of the USGS (Ref. [3]) furnishes the following overall information for water temperatures at Monticello:

Number of days surface-water temperature exceeds 80°F: zero

Median annual temperature of surface water: 45° to 49°F

Number of days surface water temperatures are between 32° and 34°F: 51 to 100 days

b) The Geological Survey Water Supply Papers Nos. 1949 (Ref. [4]) and 1956 (Ref. [5]) give daily Mississippi River water temperatures at the hydroelectric plant of NSP at Coon Rapids, five miles downstream from Anoka and at the Robert Street Bridge in St. Paul, Minnesota. Readings at the latter location had to be discarded, however, because a thermal power plant is located a short distance upstream from the recording station. The useful record of Anoka, Minnesota, is for the water year October 1962 to September 1963.

c) The U.S. Geological Survey, St. Paul office, provided data taken on selected dates at the following locations, time periods, and approximate time intervals, respectively:

Royalton, Minn.	10/63 thru 10/69	several measurements per year
Near Anoka, Minn.	8/60 thru 9/63	weekly
" " "	10/63 thru 5/66	monthly
" " "	9/66 thru 10/68	several measurements per year
Prescott, Wis.	10/63 thru 6/69	" " " "
Winona, Minn.	10/63 thru 5/69	" " " "

d) The Agricultural Research Service of the Department of Agriculture provided approximate daily average temperatures during the working day for the years 1946 through 1949. The data were read from thermograph charts recorded at Hennepin Island in Minneapolis.

e) NSP monitored Mississippi River water temperatures at Monticello, Minnesota during the summer months of 1966 through 1969. These data were made available.

f) NSP also made available average monthly water temperatures in the Mississippi River measured at its Prairie Island plant site, which is approximately 13 miles below Prescott. The data were recorded from October 1962 through June 1968.

g) The FWQA operated several water quality monitoring stations along the Mississippi River in the Minneapolis-St. Paul metropolitan area. Automatic monitoring station No. 1 is located where the Mississippi River enters the metropolitan area at mile 856.9 (NSP, Riverside Plant). Daily water temperature records for the period July 7, 1967, through June 30, 1969 are available (Ref. [6]).

These records show that Mississippi River water temperatures are subject to strong seasonal variations, as is to be expected. Daily maximum temperatures, usually occurring during July and August, have reached 84°F on rare occasions. From the middle of December to the end of February temperatures are usually near or slightly above 32°F. Spring and fall are heating and cooling periods, respectively. Temperatures show strong excursions upward and downward, the trends usually lasting for a period of several days. Temperature changes of 10°F within 24 hours have been observed during the summer months. Daily variations of 5° to 6° are not unusual. Such rapid variations are associated with the shallow water depths in the river.

River water temperatures are the result of the same heat exchange processes described in part B for the ponds. Several meteorological parameters are of importance in the relationship. Air temperature can be expected to affect river water temperatures rather strongly. To verify this point, data from FWQA Station No. 1 [6] and air temperature data from the U.S. Weather Bureau Station, Minneapolis-St. Paul International Airport for the month of October 1967 were used. These data are displayed in Fig. C-2. During that month water temperatures showed a strong decline. A correlation coefficient $R(\Delta t)$ was determined for the relationship between water and air temperatures as follows:

$$R(\Delta t) = \frac{\sum_{t=1}^{N} (T_r - T_{r,ave})_{t+\Delta t} \, (T_a - T_{a,ave})_t}{\sum_{t=1}^{N} (T_r - T_{r,ave})_t^2} \tag{C-1}$$

where N is the total number of days in the sample $(N = 31)$, t is the number of the day, T_r is the river water temperature, T_a is the air temperature, and $T_{r,ave}$ and $T_{a,ave}$ are the daily average water and air temperatures, respectively. Monthly averages could not be used because of the downward trend in the water temperature sample. Daily average values were obtained by fitting straight lines with slopes of $-0.4^\circ F$/day and $-0.5^\circ F$/day through the air and river water temperature data, respectively. Deviations of the actual data from the daily mean values could then be determined. The Δt in Eq. (C-1) is a time interval of 1,2,3,... days. The following correlation coefficients R were found as a function of the time interval:

Δt (days)	$R(\Delta t)$
0	1.18
1	0.75
2	0.19
3	0.07
4	-0.04
6	0.11
8	0.62
10	0.27

The sample calculation seems to indicate that a correlation exists between the river water and air temperatures if they are measured not more than 24 hours apart.

Another method of checking the dependence of river water temperatures on air temperatures uses the heat transfer equations given earlier. The rate of surface heat flux from Eq. (B-1) is frequently lumped into an equation of the form [1,2]

$$H_s + H_a + H_{br} + H_c + H_e = H = K(E - T_s) \qquad \text{(C-2)}$$

where K is a bulk coefficient of surface heat transfer which can be evaluated using semi-empirical equations [1,2]. Its value is usually in the range from 50 to 200 BTU $^oF^{-1}$ ft^{-2} day^{-1} [3]. As already noted, the equilibrium temperature of a well mixed body of water, E, is the temperature at which the net heat flux through the water surface is zero. By convention, H is positive when the heat flow is into the pond. At this heat transfer rate a well-mixed volume of water having a surface area A_s and a volume V will change temperature at a rate equivalent to

$$\frac{dT_s}{dt} = - \frac{KA_s}{c_p\rho V} (T_s - E) \qquad \text{(C-3)}$$

in which c_p is the specific heat of water and ρ its density. This equation can be applied to the river if it is assumed that the water temperature change is produced solely by surface heat exchange and that longitudinal dispersion, effluents, etc., have no effect. For purposes of estimation, K has been chosen as approximately 75 BTU ft^{-2} day^{-1} $^oF^{-1}$ and V/A_s has been taken as the average depth h of the river, 4 ft during October at FWQA Station No. 1. The equilibrium temperature is difficult to evaluate. It is often close to the dew point temperature of the air. In this estimation, a very rough approximation of E was obtained using values of T_A measured by the U.S. Weather Bureau at the Minneapolis-St. Paul International Airport. Starting with a water temperature of 57°F on October 1, 1967, successive values of ΔT_i, the temperature increment, were calculated for 24-hour (1-day) intervals from a finite difference form of Eq. (C-3) as follows:

$$\Delta T_i = \frac{K}{c_p\rho h} (T_{a,i} - T_{s,i})\Delta t \qquad \text{(C-4)}$$

River temperatures were calculated using the recursion formula

$$T_{s,i} = T_{s,i-1} + \Delta T_i \qquad \text{(C-5)}$$

The results are shown by the dashed curve in Fig. C-2. The very simple formula used predicts the trends in Mississippi River water temperature quite well, indicating a strong influence of air temperatures and a fast response of water temperatures to these air temperatures. The absolute values of the predicted water temperatures are not correct because of the assumptions involved and could be changed by taking a different value for K.

The previous discussion must lead to the conclusion that Mississippi River water temperatures near Monticello fluctuate quickly, strongly, and often. The heating water temperature for the experimental ponds will show the same fluctuations. This represents a rather severe complication of the problem.

Mean monthly Mississippi River water temperatures were determined from records available for six stations: Royalton, Anoka, FWQA Station No. 1, Prescott, NSP Prairie Island, and Winona. The values obtained were not identical for several reasons, including the short length of all records and the difference in times of temperature reading. No systematic differences between stations could be found. Figure C-3 shows the range for the mean monthly values at the six stations. Values for Monticello were estimated taking into consideration the scatter of data, the length of the record, and the distance of the station from Monticello. The estimated mean monthly values for Monticello are shown in Table C-1. Deviations of daily maxima and minima from the monthly mean are numerous. It would have been desirable to determine the magnitude and frequency of these deviations, but the records were much too short for this purpose. To facilitate an appreciation of the order of magnitude, the graphical representations for the two most complete records (FWQA Station No. 1, two years of record, and USGS Station, Anoka, six years of record) were used and envelope curves were drawn through the extreme values. One example of the results is given in Fig. C-4. Recorded deviations from mean monthly values amount to as much as +13°F and -10°F except during the winter months. On the basis of these results extreme monthly Mississippi River water temperatures have been estimated and are also shown in Table C-1. The procedure followed was to plot the mean monthly values on the 15th of each month, to connect these points with a straight line, and to draw a tangent with the same slope as the straight line to the envelope curve for the same month. The distance from the line connecting the means to the tangent was considered to be the maximum or minimum deviation and was added to or subtracted from the monthly mean.

The reported deviations between Mississippi River temperature extremes at Monticello, Minnesota, and monthly mean river water temperatures are substantially higher than those reported, for example, for the Columbia River in Ref. [7], wherein values of +6°F and -4°F are given.

1.2 Groundwater Temperatures

The depth from which the ground water will be drawn is presently unknown. The NWQL has reported that groundwater temperatures will be in the range from 45°F to 55°F.

According to verbal information received from the USGS St. Paul office, groundwater temperatures above 50 ft of depth vary with time of year; below 50 ft of depth they are likely to be constant throughout the year. This information is based on measurements in an outwash plain in Ottertail County, Minnesota. The temperature there measured below 50 ft of depth was 45°F.

According to a well drilling company, well-water temperatures in central Minnesota in summer are often close to 50°F.

Reference [23] contains the following statement regarding the Minneapolis-St. Paul metropolitan area:

> Water temperatures in the artesian aquifers are generally within the range of 48° to 55°F with the higher temperatures generally occurring at greater depths. Little if any seasonal variation has been noted. Temperatures in the drift are sometimes slightly lower but are more variable, being responsive to temperatures at or near the ground surface at the time recharge occurs. The generally low temperature of ground water makes it especially desirable for cooling purposes and its lack of variability is important for some industrial use.

In summary, a groundwater temperature near 50°F can be anticipated, and this value has been chosen for design purposes.

2. Meteorological Data at Monticello, Minnesota

Since there is no weather station at Monticello, Minnesota, records obtained at the other stations shown in Fig. C-5 have been assembled and used.

2.1 Solar Radiation

The nearest station for which solar radiation measurements are available appears to be at St. Cloud, Minnesota. Records for the period July 1952 through June 1966 (15 years) were analyzed by Baker and Haines [9]. Tables giving weekly mean values of measured radiation (p. 221) and other tables giving the frequency of weekly radiation values by increments of 100 langleys (1 langley = 3.685 BTU ft^{-2}) were used. Weekly mean values were transformed into monthly means by averaging over four- or five-week periods. Another table was used to determine the approximate value of monthly solar radiation for 85 per cent and 15 per cent frequency. Interpolation between weekly averages produced the approximate results shown in Table C-2. The mean monthly values are repeated in Appendix B-1, column (1).

2.2 Air Temperature

Air temperature data could be taken from various stations surrounding the Monticello site. For the sake of consistency the records for St. Cloud were examined first. Mean monthly air temperatures were readily available in Ref. [19]; they are reproduced in column (2) of Appendix B-1. Climatological data sheets for 41 years of record (1928 through 1968) were examined and the highest and lowest daily air temperatures in each month were recorded. The 41 annual maxima and minima were subjected to a frequency analysis, and the results shown in Figs. C-6 and C-7 were obtained. The values refer to one day in every year (annual series of data). Similarly, temperature differences ΔT between daily high and low air temperatures were selected for each month. The highest value of ΔT for each year was retained. Frequency analysis produced the results shown in Fig. C-8. The results shown suggest that extreme daily air temperature fluctuations are produced by various meteorological phenomena such as cold fronts, radiative heating and cooling, and precipitation and that the frequency characteristics associated with these may differ.

2.3 Wind Velocity and Direction

General information on the wind conditions at the Monticello site was gathered from various sources. Reference [10] indicates that the average annual wind velocity would be 11.4 mph at 25 ft above the ground. More recent data [11] propose a value of 10.7 mph at 21 ft above the ground. Considering the velocity distribution of winds, the two values can be considered to be in reasonable agreement for the purposes of this study. Mean monthly values were also obtained from Ref. [11]. They are reproduced in column (3) of Appendix B-1.

A frequency analysis of 35 years of U.S. Weather Bureau records (1934 through 1968) for the station at Minneapolis produced the frequency distribution shown in Fig. C-9. The graph includes winds from all directions. The data shown represent an annual series using the highest value for every year. The graph can be used to determine the approximate magnitude of winds of low (rare) probability of occurrence.

Monthly maxima of wind velocities were used to determine the prevailing wind directions for strong winds. The resulting wind rose is shown in Fig. C-10. It was found that 41 per cent of the strongest winds blow from the northwest, while 18 per cent blow from the west. Only 4 per cent of the strong winds blow from the east.

The frequency of occurrence of winds of all magnitudes assembled in speed groups and by direction can be obtained from Ref. [11]. Reference [11] confirms that the high-velocity winds occur mostly from the northwest. Very low velocity winds, up to approximately 3 mph, seem to blow fairly uniformly from all directions. Those in the intermediate range from approximately 4 to 12 mph show a slight prevalence of southeasterly or northwesterly directions.

A seasonal wind shift occurs regularly. From November through April the wind direction is most frequently from the northwest. During May through October winds from the south and southeast prevail. This information will be useful if the ponds are to be protected from winds by hedges, fences, trees, walls, or other obstacles.

2.4 Humidity

The amount of moisture accumulated in the air has a significant effect on evaporation from a water surface, and for this reason relative humidity data were included in the survey of meteorological data. Long-range mean monthly averages of the local relative humidity at noon were found in two charts contained in Ref. [12]. The average relative humidity at Monticello is near 74 per cent in January and near 53 per cent in July.

Water vapor pressure data, which are related to relative humidites, are contained in Refs. [10] and [13]. Mean monthly vapor pressures observed at the U.S. Weather Bureau station in Minneapolis and reduced to equivalent vapor pressures about 25 ft above the ground are given in Ref. [10] and reproduced in Table C-3. The data from Ref. [10] are also reproduced in column (4) of Appendix B-1 for later use. The psychrometric summary (Ref. [13]) gives a much more detailed account for a 10-year period (1951 through 1960). It provides a tabulation of wet bulb depressions versus dry bulb temperatures; a tabulation of occurrences of dry bulb, wet bulb, and dew point temperatures separately; statistical data for the individual elements of relative humidity; dry bulb, wet bulb, and dew point temperatures; and finally, information on the mean number of hours of occurrence for six ranges of dry bulb, wet bulb, and dew point temperatures. Data extracted from it appears in Table C-4. The mean monthly vapor pressures reproduced in the last column of Table C-3 were obtained using the dry bulb temperatures and relative humidites shown in Table C-4. The results from Refs. [10] and [13] are comparable for the purposes of this study.

2.5 Precipitation

According to charts given in Ref. [12], page 118, the total annual precipitation values for a site near Monticello are as shown in Table C-5. Monthly maximum, normal, and minimum total precipitation values are given in Ref. [14]. Values for St. Cloud are reproduced in Table C-6, and the normal values are also reproduced in column (5) of Appendix B-1 for later reference. It can be seen that a large percentage of the total precipitation occurs in summer, while the winter months of December through February see little precipitation. The frequency of days with precipitation of selected amounts are analyzed in Ref. [12], page 121. Table C-7 gives selected values for Minneapolis.

The relationship between the amount of precipitation and the duration of individual storms is shown in Fig. C-11. Graphs in the Rainfall Frequency Atlas [15] were used to find the curves for return periods of 100 and 50 years at Monticello. For comparison, measurements for two severe storm events reported in Ref. [16] as well as maximum values recorded in the U.S. and in the world have been added to Fig. C-11. Total amounts of precipitation can be converted into intensities if the durations are known. Values from Ref. [15] gave the results shown in Fig. C-12. These results are quite similar to those given in Ref. [12], p. 122 for Minneapolis.

Precipitation in the form of snow has a heat content different from that of rain. Therefore some information on snowfall had to be collected separately from that on rain. Monthly totals of maximum and normal snowfall were extracted from Ref. [14] and are reproduced in Table C-8. The frequency of occurrence of snowstorms of various strengths at Minneapolis has also been given in Ref. [14]. For the purpose of this study the total accumulation of snow is of less interest than the water content in each snowfall event. Therefore snowfall data taken at St. Cloud from 1949 to 1968 and reported in the Climatological Data Sheets of the Weather Bureau were analyzed. The daily maximum snowfall of each year was identified. Its water content was found in the climatological data sheets assuming that the total precipitation for that day was in the form of snow. Return periods were calculated and plotted in Fig. C-13.

2.6 Evaporation

The loss of water from a Minnesota lake or pond due to evaporation depends on such factors as its temperature regime and its vegetation. Mean monthly values of evaporation from shallow lakes and reservoirs located near Monticello, Minnesota, under natural temperature conditions were interpolated from graphs in Ref. [10] and are shown in Table C-9.

Table C-1

MISSISSIPPI RIVER WATER TEMPERATURES

Estimated from available records

Month	Monthly Mean °F	Daily Max °F	Daily Min °F
Jan	33	37	31
Feb	33	38	31
Mar	35	47	31
Apr	44	59	38
May	59	72	49
June	68	80	57
July	76	85	67
Aug	73	86	67
Sept	65	77	56
Oct	52	68	44
Nov	40	52	32
Dec	34	40	31

Table C-2

SOLAR RADIATION DATA FOR ST. CLOUD IN LANGLEYS PER DAY

(Basic data from Ref. [9])

		Probability of Exceedence	
Month	Monthly Mean	85 per cent	15 per cent
Jan	174	105	263
Feb	269	152	365
Mar	357	200	500
Apr	429	190	618
May	493	250	710
June	539	300	738
July	564	385	738
Aug	499	325	663
Sept	340	145	515
Oct	241	100	365
Nov	147	50	250
Dec	122	45	183

Table C-3

MEAN MONTHLY VAPOR PRESSURES IN INCHES OF MERCURY

Month	from [10]	from [13]
Jan	0.074	0.057
Feb	0.082	0.074
Mar	0.125	0.104
Apr	0.197	0.192
May	0.301	0.310
June	0.456	0.457
July	0.523	0.555
Aug	0.436	0.542
Sept	0.386	0.368
Oct	0.246	0.245
Nov	0.146	0.134
Dec	0.094	0.082

Table C-4

PSYCHROMETRIC SUMMARY - MEAN MONTHLY VALUES (from [13])

Month	Rel. Hum. per cent	Dry Bulb °F	Wet Bulb °F	Dew Point °F
Jan	74.4	13.7	12.3	6.9
Feb	72.9	19.4	17.9	11.7
Mar	69.9	27.7	25.5	18.4
Apr	61.1	46.2	39.8	31.7
May	59.8	59.0	50.8	43.1
June	65.5	68.1	60.3	54.7
July	67.3	73.2	65.1	60.5
Aug	69.7	71.5	64.1	60.0
Sept	68.4	60.9	54.3	49.2
Oct	66.8	49.5	44.2	38.0
Nov	72.8	32.4	29.6	24.1
Dec	77.6	20.6	19.3	14.5
Annual Mean	68.9	45.2	40.3	34.4

Table C-5

TOTAL ANNUAL PRECIPITATION IN INCHES (from [12])

	Probability of Exceedence	
	2 %	20 %
Maximum	37.7	30.1
Minimum	15.1	21.9

Table C-6

MONTHLY TOTAL PRECIPITATION AT ST. CLOUD FOR PERIOD 1931 - 1960 IN INCHES

(from Ref. [14])

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Maximum	2.12	2.76	2.61	3.62	6.80	9.34	8.00	7.55	6.12	4.24	4.02	1.80	
Normal	0.72	0.80	1.28	2.02	3.51	4.49	3.26	3.73	2.41	1.64	1.33	0.73	25.92
Minimum	0.02	0.09	0.27	0.25	0.88	0.80	0.94	0.42	0.07	0.07	0.01	0.07	

Table C-7

FREQUENCY OF PRECIPITATION AMOUNTS AS A PERCENTAGE OF TOTAL NUMBER OF DAYS WITH PRECIPITATION FOR MINNEAPOLIS. RECORD PERIOD 1951 - 1960 (from [12])

Amount of Precipitation in Inches	Per cent of Days with Indicated Amount
Trace	42.1
0.01	8.4
0.02 to 0.09	20.5
0.10 to 0.24	12.1
0.25 to 0.49	8.9
0.50 to 0.99	5.3
1.00 to 1.99	2.1
More than 2.0	0.5

The total number of days with precipitation was 52.1.

Table C-8

MAXIMUM AND NORMAL SNOWFALL AT ST. CLOUD FOR PERIOD 1931 - 1960 IN INCHES

(from [14])

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Maximum	18.2	20.0	51.7	11.1	3.3	0.0	0.0	0.0	1.8	4.1	26.9	21.8	
Normal	6.5	7.7	11.5	2.8	1.0	0.0	0.0	0.0	1.0	0.4	6.3	7.0	42.4

Table C-9

MEAN MONTHLY EVAPORATION FROM WATER SURFACE UNDER NATURAL TEMPERATURE CONDITIONS IN INCHES OF WATER (from [10])

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Evaporation	0.33	0.43	0.91	1.7	3.2	4.4	6.0	5.8	4.6	3.0	1.3	0.43

These values total 32.10 inches.

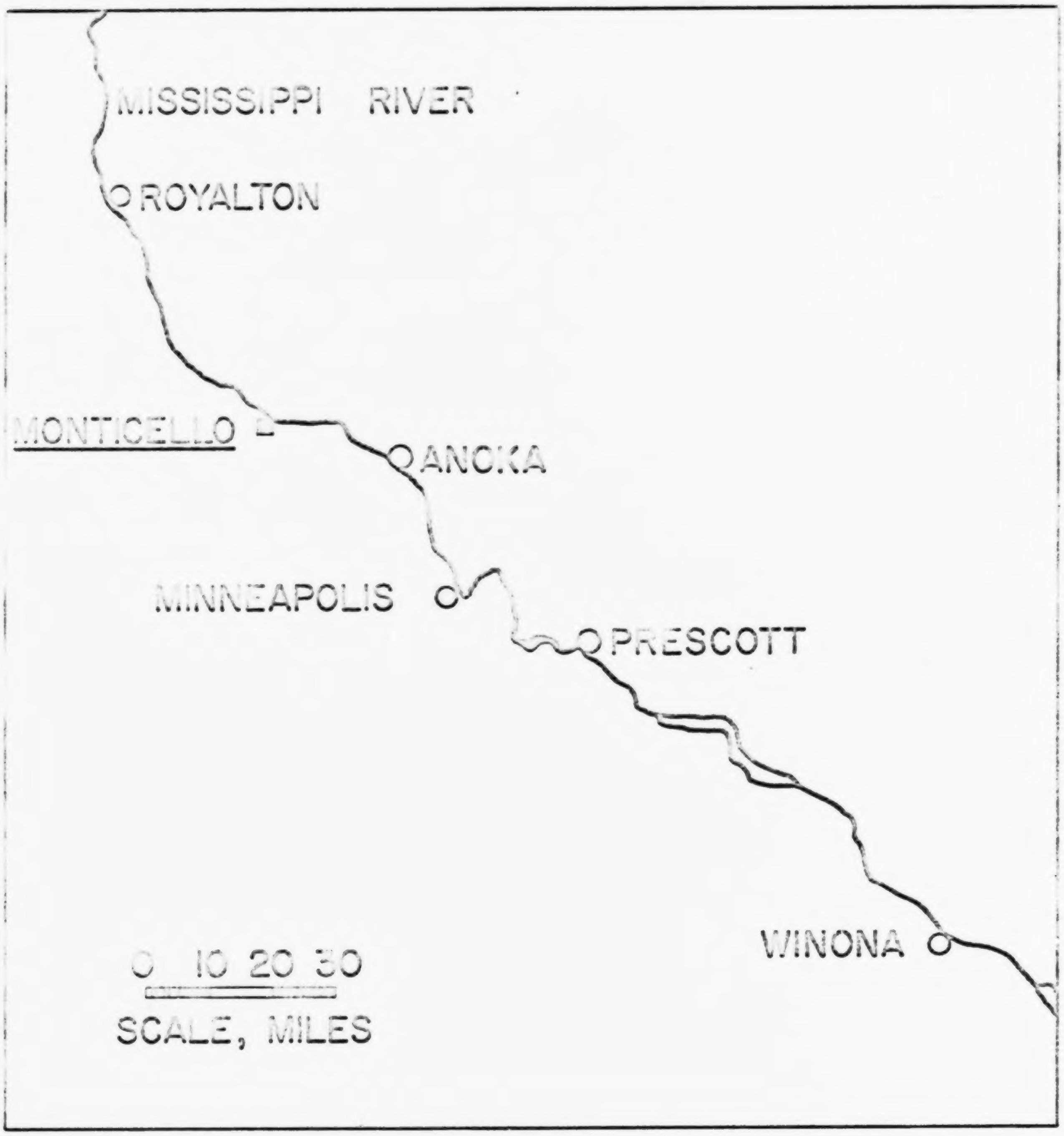

MISSISSIPPI RIVER
ROYALTON
MONTICELLO
ANOKA
MINNEAPOLIS
PRESCOTT
WINONA
0 10 20 30
SCALE, MILES

Fig. C-1 - Locations on the Mississippi River for which Water Temperature Records are Available

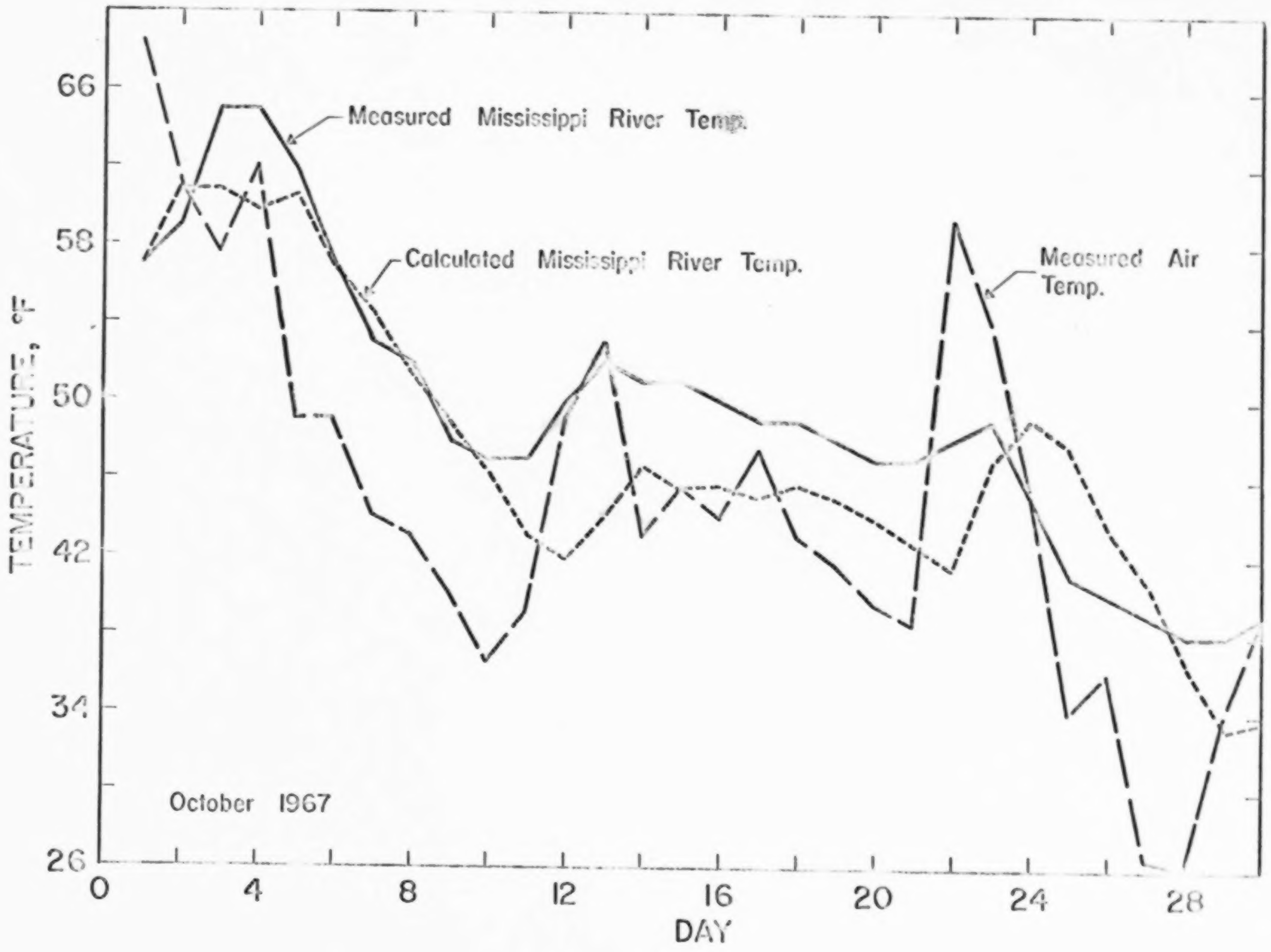


Fig. C-2 – Case Study of Mississippi River Water Temperature Record

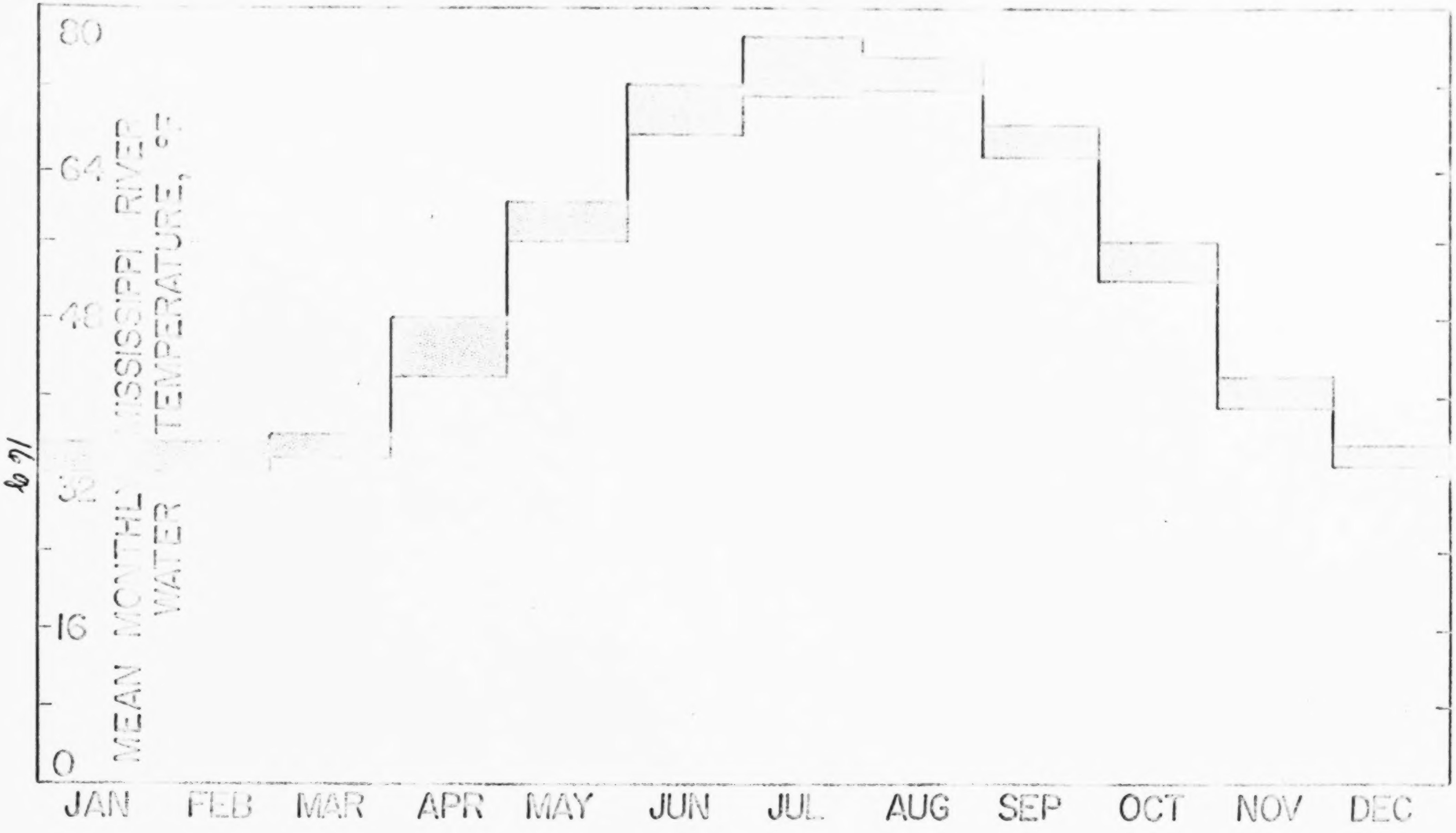


Fig. C-3 -- Mean Monthly Mississippi River Water Temperatures

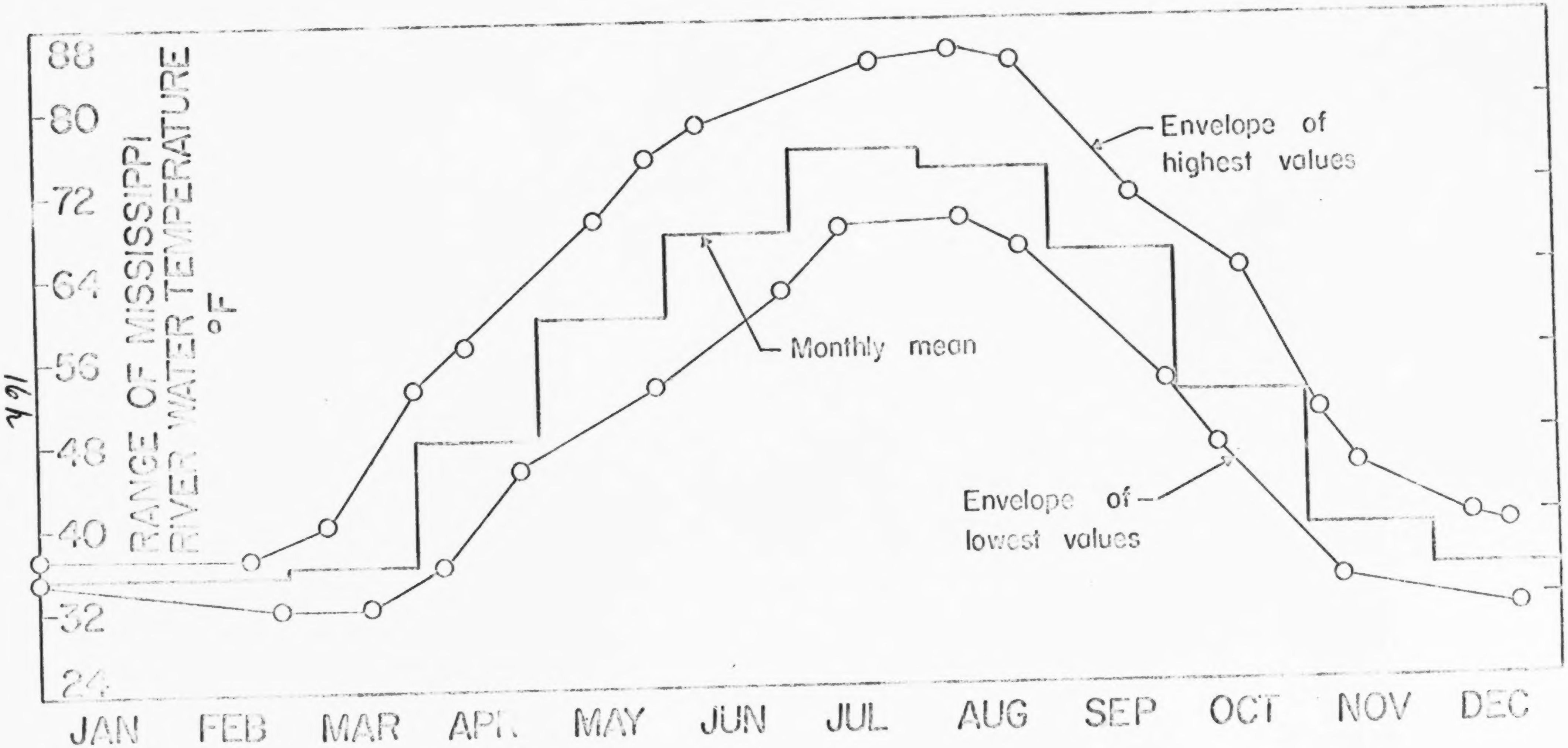


Fig. C-4 - Samples of Mississippi River water temperatures derived from two years of water temperature records (July 7, 1967 to June 30, 1969). Measurements were taken at FWQA Station No. 1 near the upstream city limits of Minneapolis.

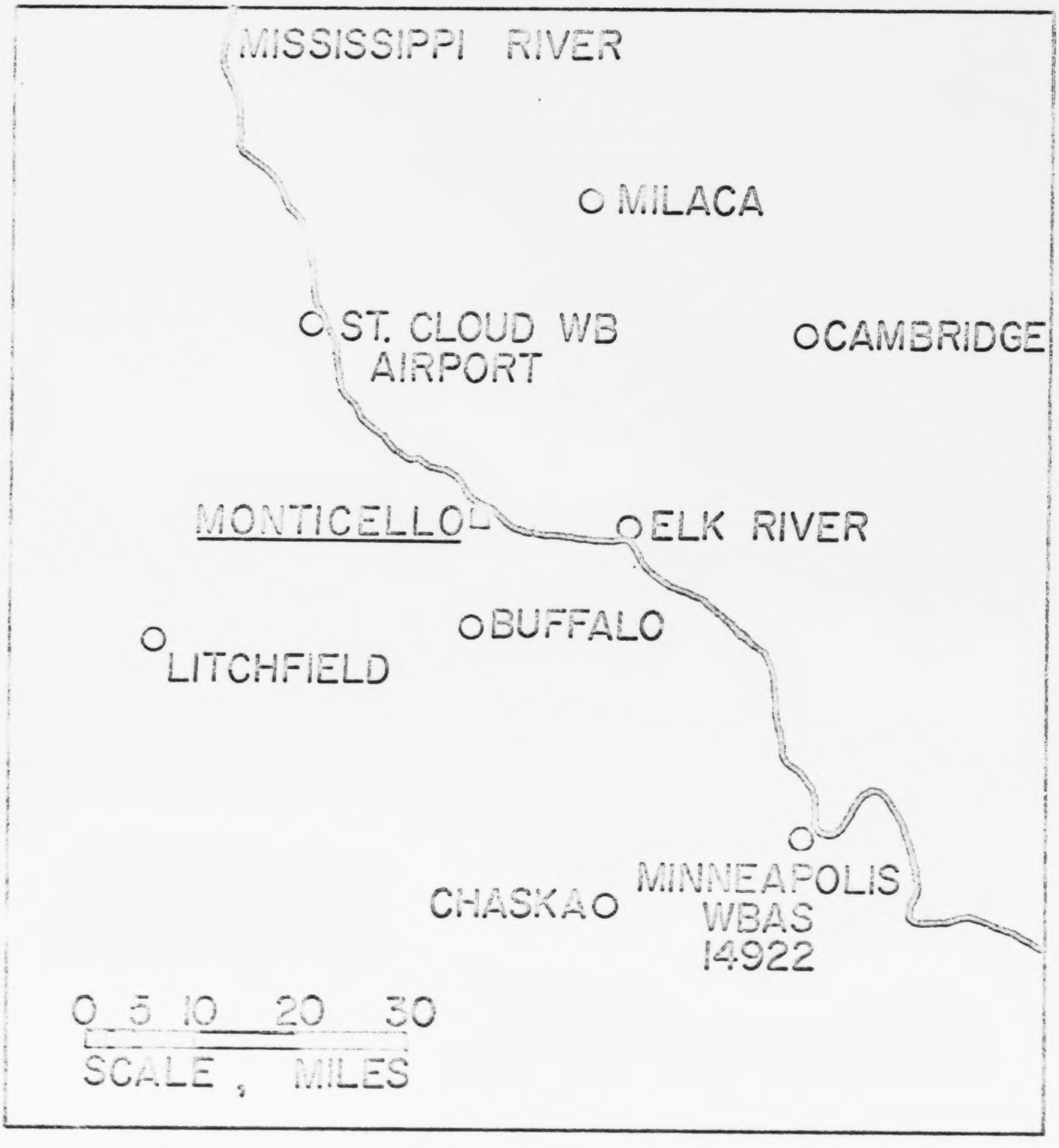

MISSISSIPPI RIVER
MILACA
ST. CLOUD WB AIRPORT
CAMBRIDGE
MONTICELLO
ELK RIVER
BUFFALO
LITCHFIELD
MINNEAPOLIS WBAS 14922
CHASKA
0 5 10 20 30
SCALE, MILES

Fig. C-5 - Map of U.S. Weather Bureau stations near the site of the Experimental Ponds at Monticello, Minnesota

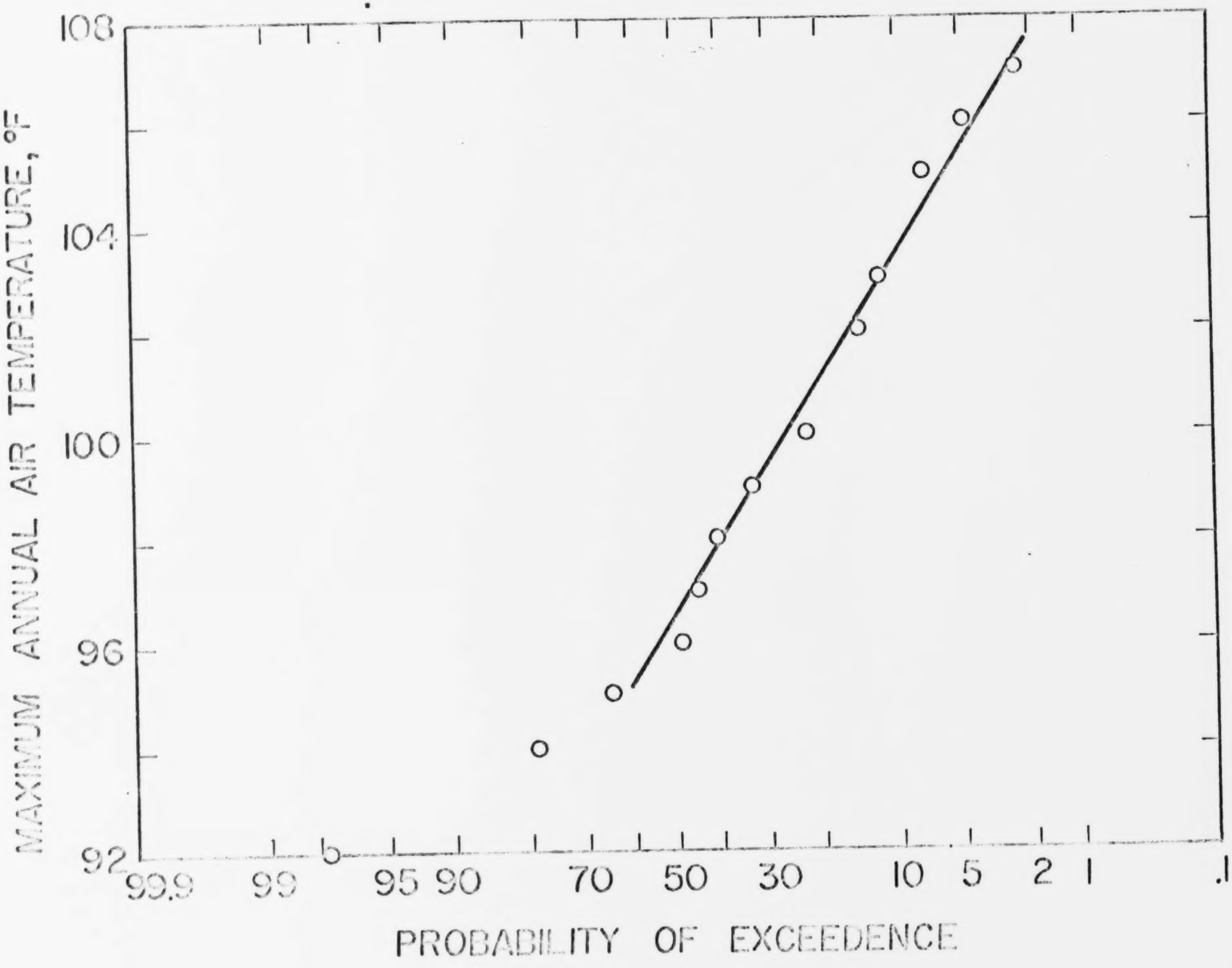


Fig. C-6 - Frequency Diagram for Maximum Annual Air Temperature

16K

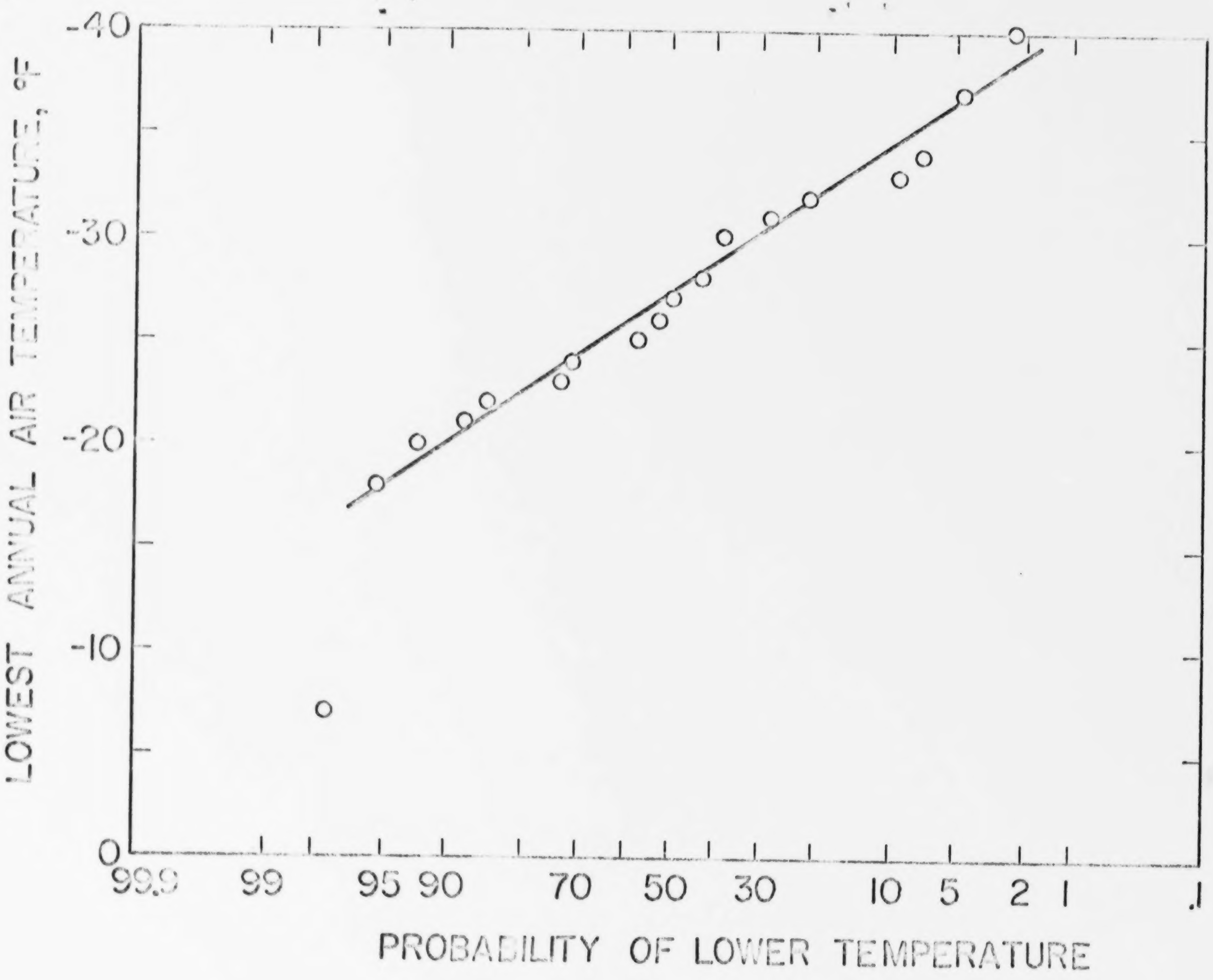


Fig. C-7 - Frequency Diagram of Lowest Annual Air Temperature

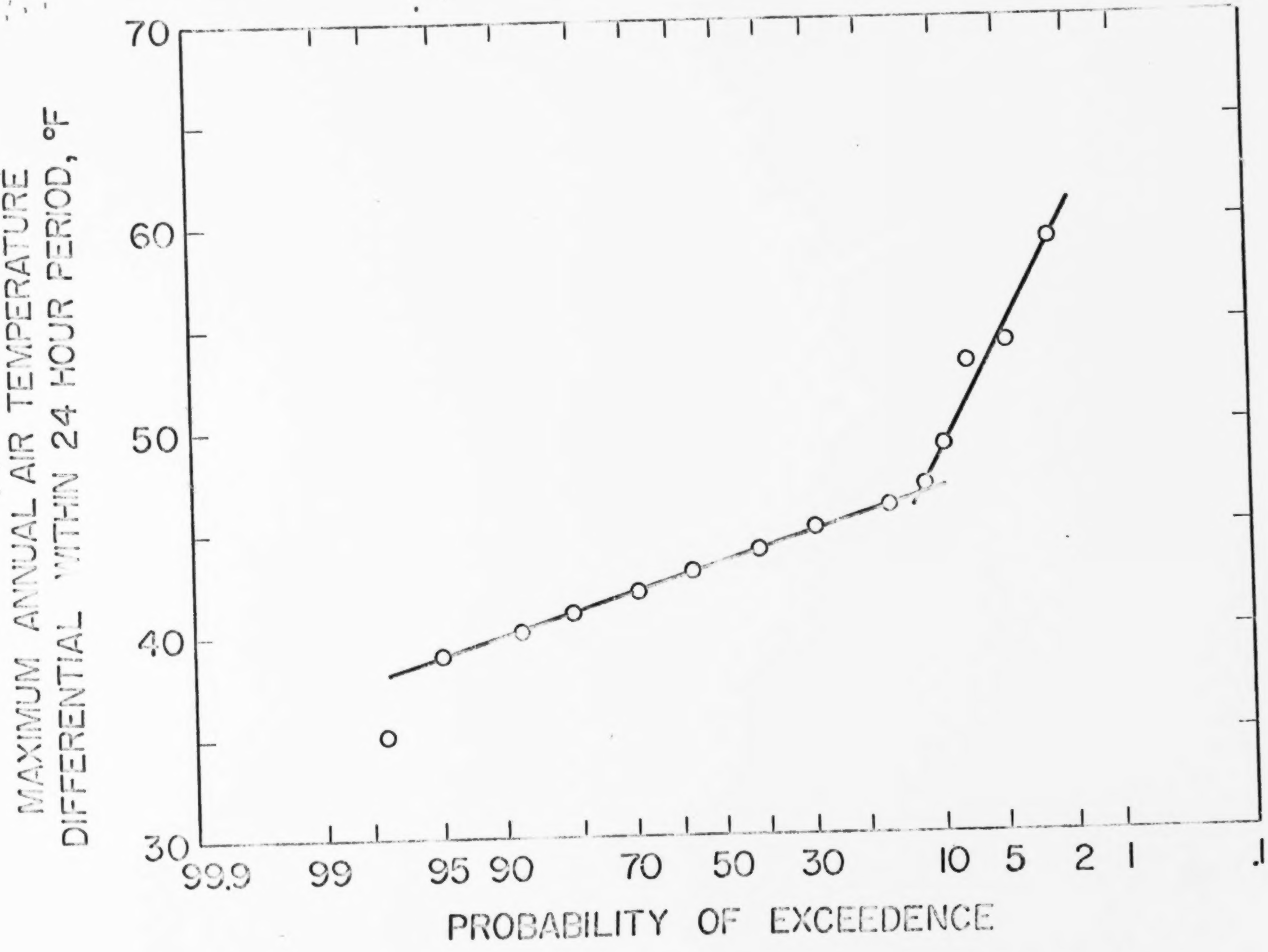


Fig. C-8 -- Frequency Diagram of Largest Annual Temperature Differential within 24 hours

1491

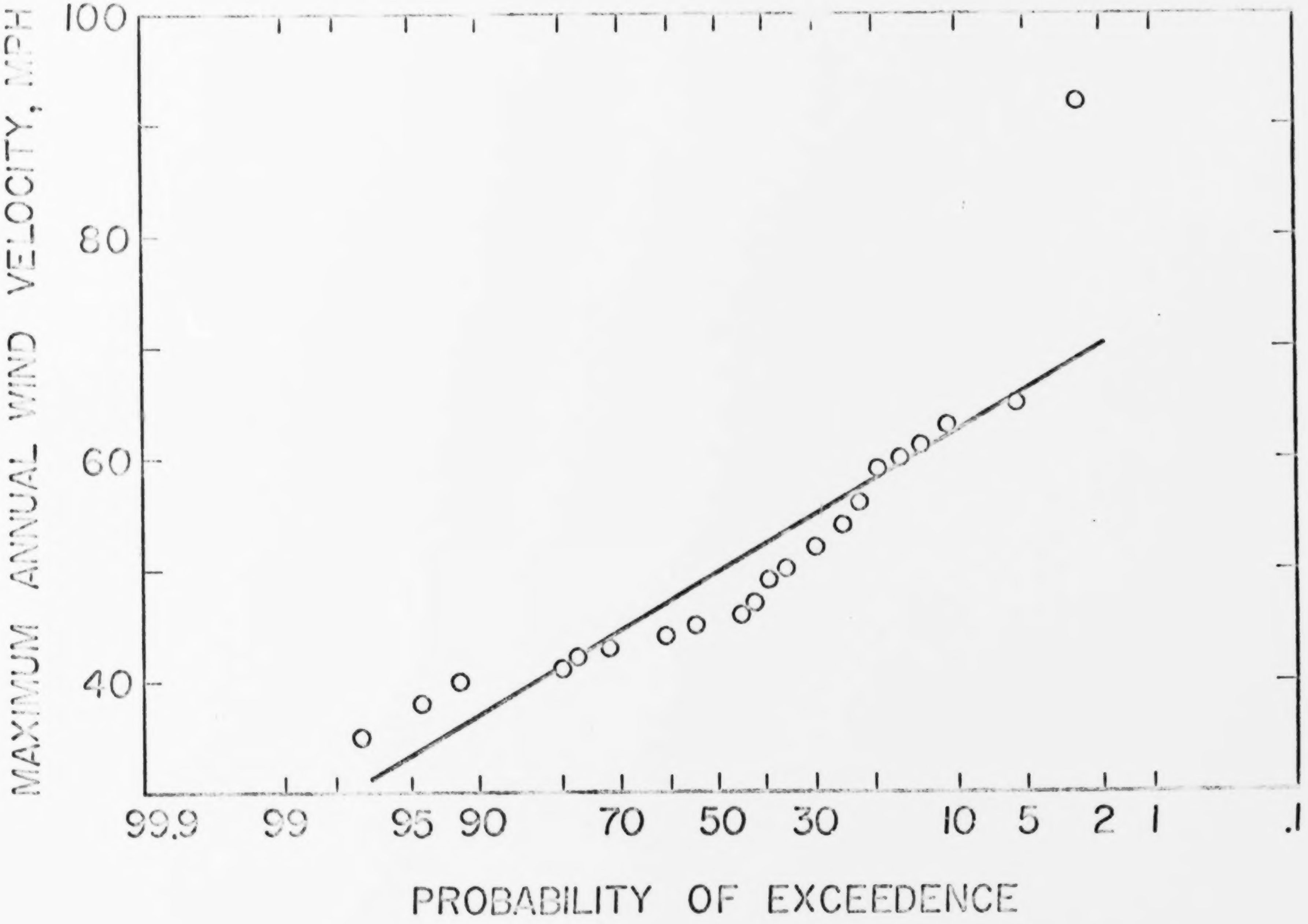


Fig. C-9 - Frequency Diagram of Maximum Annual Wind Velocity

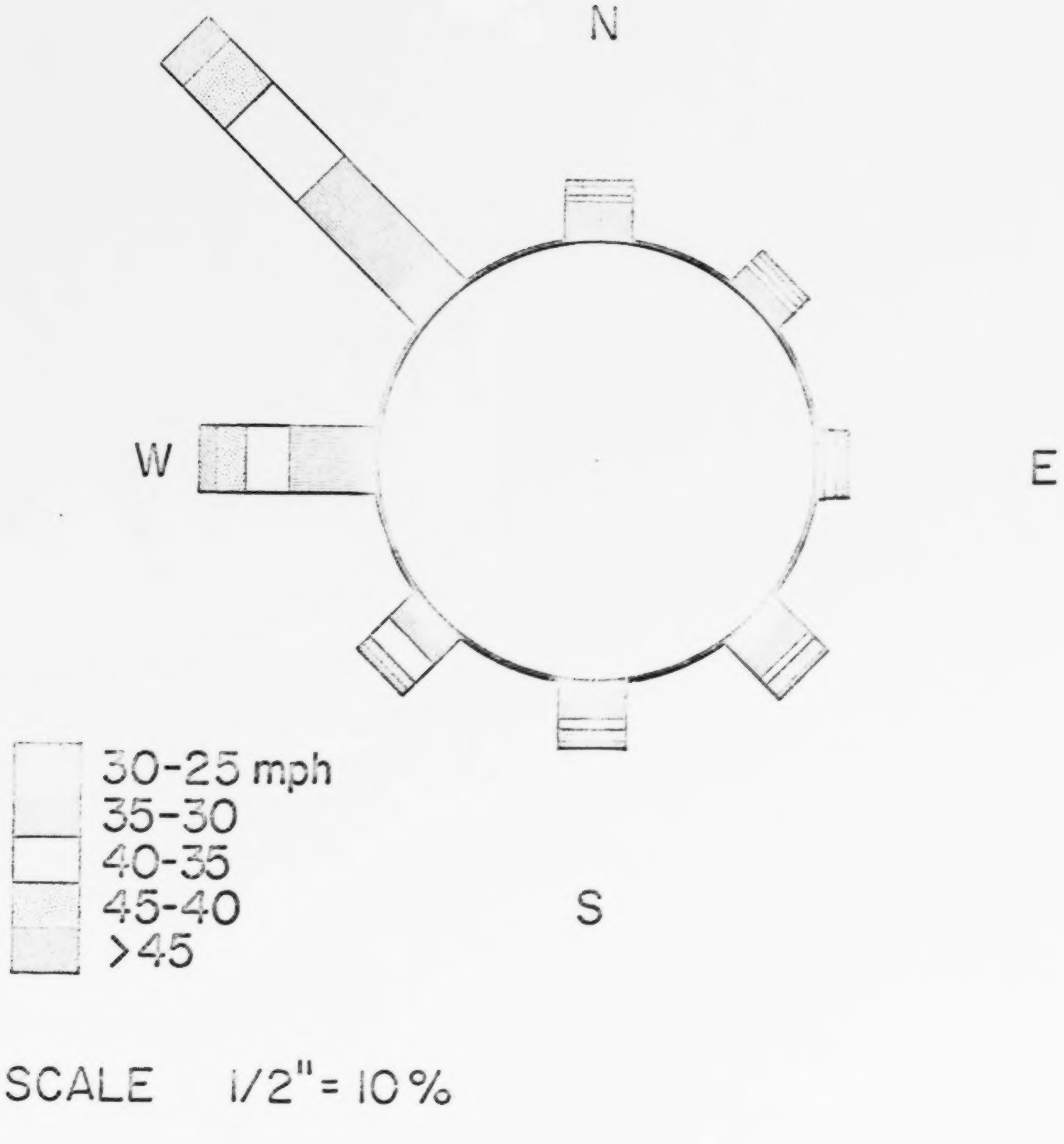


Fig. C-10 - Wind Rose of Monthly Maximum Wind Velocities

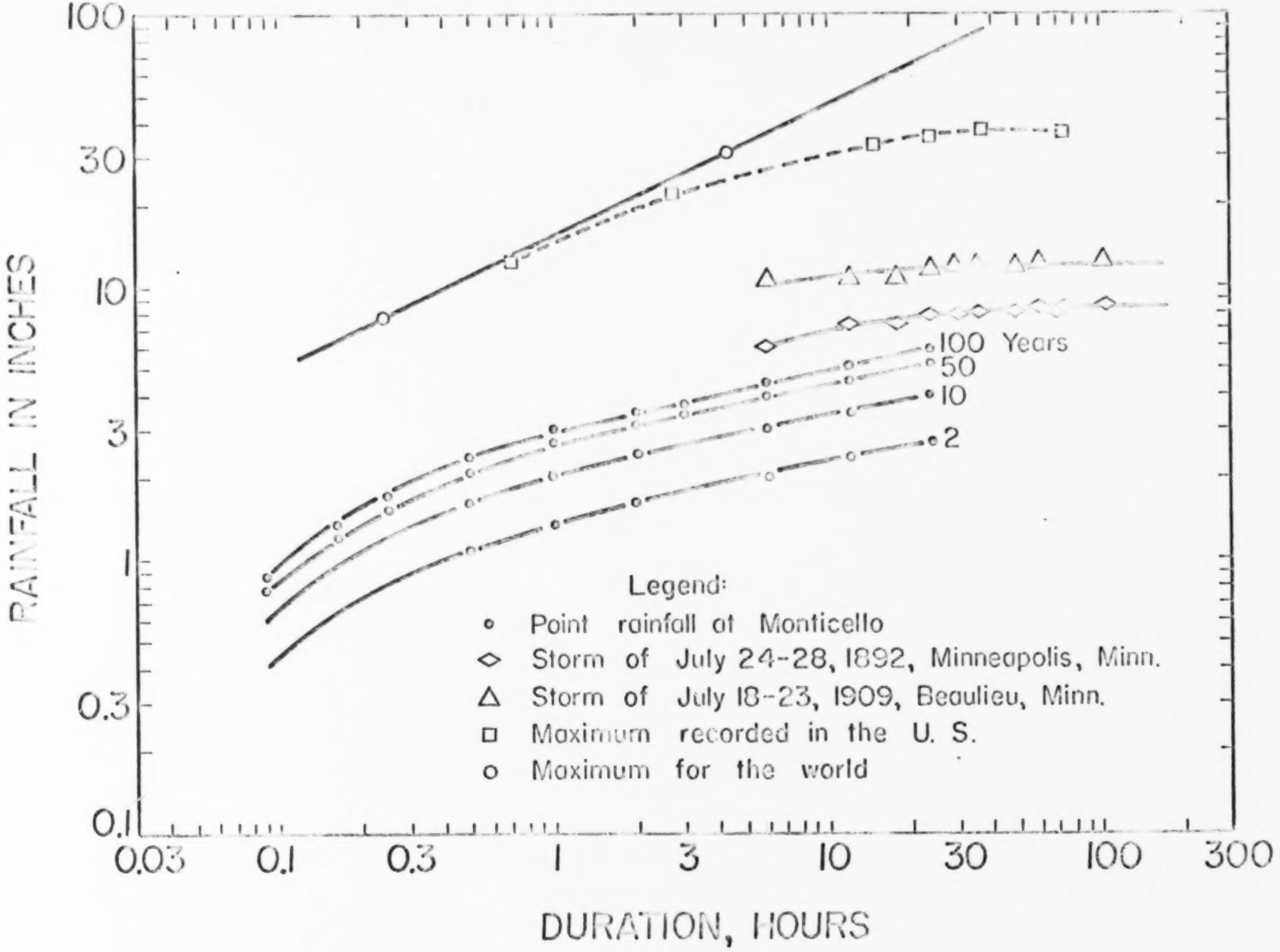


Fig. C-11 - Precipitation Duration Frequency Diagram

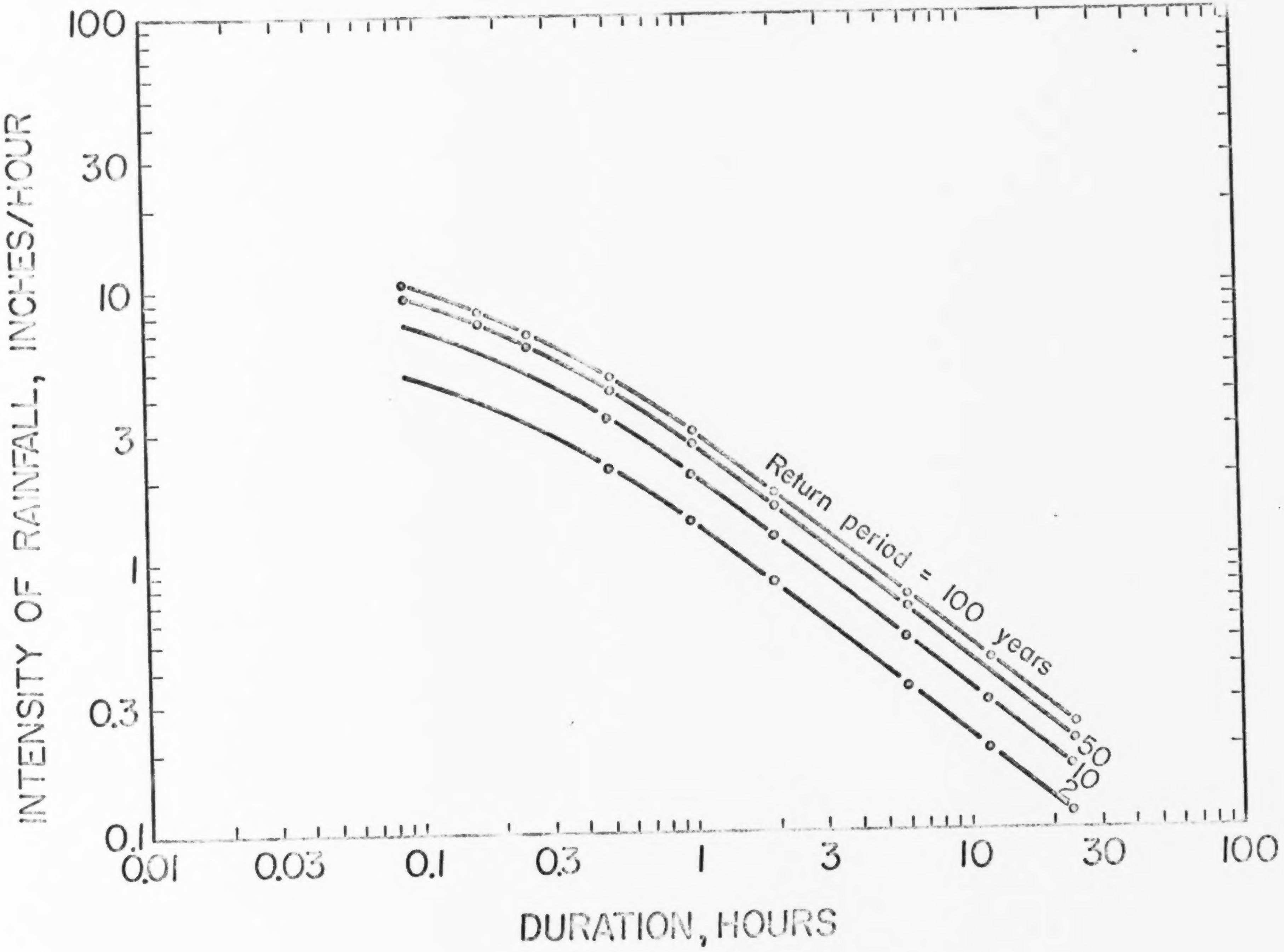


Fig. C-12 -- Rainfall Intensity-Frequency Diagram

16 Q

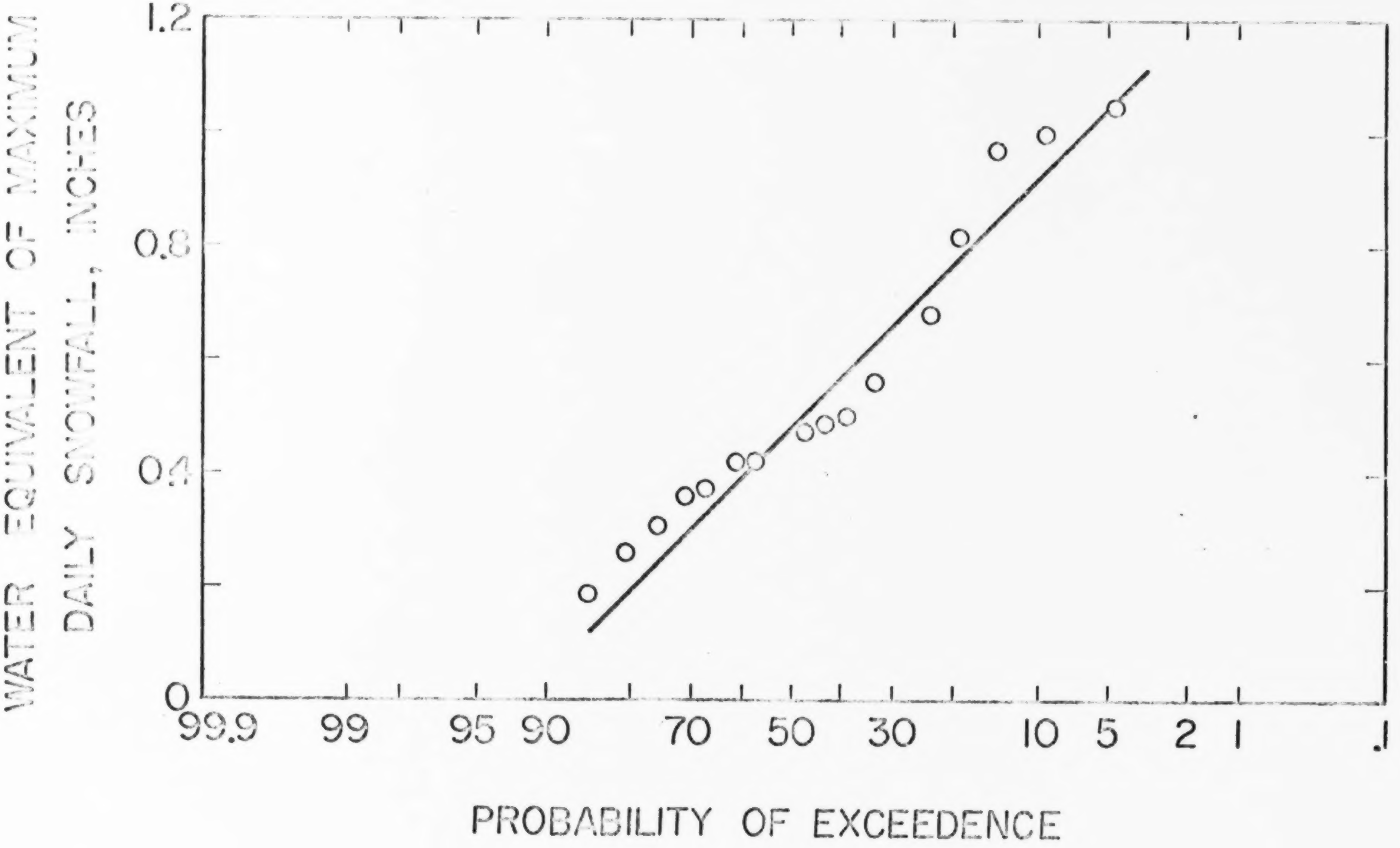


Fig. C-13 - Snowfall Frequency Diagram

D. HEAT BUDGET OF THE PONDS

The heat exchange between the ponds and their environment may occur through the water surface or through the ground. As will become apparent, however, the main flux of heat takes place through the water surface, and the bulk of this chapter will deal with heat exchange through the surface. An appraisal of the heat fluxes through the bottom will be undertaken later in the chapter.

1. Heat Exchange through the Water Surface

1.1 Application of the Basic Equations

The basic mechanisms and equations for heat transfer through a water surface have been outlined in Part B. They will now be discussed and reduced to the form in which they were applied to the present problem. Equation (B-1) has seven terms. The last term, which has to do with water addition to the pond, depends on the final design of the pond. It can and will be evaluated later, because it depends linearly on pond water temperature, as is shown by Eq. (B-9). Evaluation of the remaining six terms in Eq. (B-1) required the use of Eqs. (B-3) through (B-8). Pond water temperature is also necessary in evaluating (B-4), (B-5), and (B-6), and the final evaluation of these must also await specification of the pond temperature.

From Ref. [2] the following numerical values for the constants were obtained:

Emissivity of water	$\epsilon_w = 0.97$
Stefan-Boltzmann constant	$\sigma = 4.15 \times 10^{-8}$ BTU ft^{-2} day^{-1} $^{o}R^{-4}$
Absolute temperature	$\Delta = 460\,^{o}R$
Constant in Bowen Ratio	$c_1 = 0.0102$ in Hg $^{o}F^{-1}$

In addition, the emissivity of air was set at $\epsilon_a = 0.97$.

The function $f(U,\psi)$, which includes the overall effects of wind on the turbulent heat exchange process at the water surface, was taken as

$$f(U,\psi) = a + bU \qquad \text{(D-1)}$$

In this equation a and b have to have appropriate units so that the final result of Eqs. (B-5) and (B-6) will have the units of heat fluxes. The value of U is usually given in mph. The coefficients a and b can be derived from empirical evaporation formulas. Values from three sources are given in Ref. [2]. It is probably fair to say that the turbulent exchange processes at the water surface are quite complex and not completely understood at the present time. As a consequence the proposed values of a and b differ widely. Because there is a chance that regional differences in the values of a and b exist, the values derived from Meyer's evaporation formula (ref. [10]) based on data from Minnesota and surrounding states were applied. Meyer used his equation and meteorological data to predict lake levels on Lake Minnetonka, 25 miles west of Minneapolis and approximately 40 miles from the site of the ponds. His predictions checked the observed lake levels closely, and his conclusion was (ref. [10]) as follows: "If there were anything radically wrong with the Meyer Evaporation Formula, the level of Lake Minnetonka, computed from day to day under such varied weather conditions as those shown in Fig. 9, would not check the observed lake level as closely as it does."

In a more recent study [17] using available data from power plant cooling ponds a wind function of the form

$$f(U,\psi) = (a + bU + cU^2) \qquad \text{(D-2)}$$

has been proposed. Table D-1 summarizes the values of a, b, and c given by various authors. The values should be used with windspeeds expressed in mph and vapor pressures in mm Hg and will then produce heat fluxes in BTU ft^{-2} day^{-1}. A graphical comparison of the five equations is given in Fig. D-1. For wind speeds between zero and 16 mph the first two equations (Meyer and Brady) give results which differ by no more than 20 per cent. None of the proposed equations appears to have been derived from or verified at high windspeeds, where evaporative heat losses are particularly large. It should also be noted that most of these equations were derived for application in cooling pond design, where water surface areas are considerably larger than one-fourth acre. The short wind fetch in the experimental ponds may have effects which are difficult to foresee.

In order to evaluate Eq. (B-5) it is also necessary to know the water vapor pressures, which can be determined from temperature and relative humidity. Saturation vapor pressures are given in tabular form, for example, in Ref. [18], p. 64, as a function of temperature. Then actual vapor pressures for the air, e_a, can be computed if the relative humidity f is known from

$$e_a = 100\, f \cdot e \qquad \text{(D-3)}$$

where e is the saturation vapor pressure at the given air temperature. Equations (B-7) and (B-8) contain the following constants:

Density of water	$\rho = 62.4\ lb_m\ ft^{-3}$
Specific heat of water	$c_p = 1\ BTU\ lb_m^{-1}\ {}^oF^{-1}$
Specific heat of ice	$c_{p,s} = 0.46\ BTU\ lb_m^{-1}\ {}^oF^{-1}$
Latent heat of fusion	$L_f = 144\ BTU\ lb_m^{-1}$

For lack of better information it was assumed that the temperature of precipitating water T_p equalled the air temperature T_a, but it will be shown later that precipitation contributes negligibly to pond temperature regime. The freezing temperature or fusion temperature T_f was of course 32^oF.

Equations (B-1) and (B-3) through (B-8) were programed to facilitate numerical evaluation. Input values were meteorological parameters such as those specified in Part C and the pond water temperatures, yet to be discussed, and the saturation vapor pressure associated with them.

It must be recognized that the parameters solar radiation H_s, pond water temperature T_s and associated saturation vapor pressure e_s, air temperature T_a, wind velocity U, vapor pressure in the atmosphere e_a, and precipitation intensity I are all variables with time. The relationship between each of these parameters and time is very complex and apparently not accessible to analytical description. Furthermore, correlations of a complicated nature exist between them; that is, it is doubtful that in a group they can be treated as statistically independent when several of them have to be considered at the same time. Nevertheless, extreme values of these parameters have often been treated separately as randomly distributed variables, and useful results have been obtained with this assumption.

In the following paragraphs, the basic equations will be used to compute mean monthly values of net heat fluxes through the water surface based on the mean hydrologic and meteorologic data. Subsequently, frequency distributions of surface heat losses for each month will be obtained by making additional simplifying assumptions, and these will be applied to calculating extreme heat fluxes.

1.2 Mean Monthly Pond Temperatures

The temperature under which each pond will be operated has to be specified at this point. As outlined in part B, this can be done only by making an initial assumption for the pond water temperatures and verifying the assumption later when all heat losses have been calculated. The water temperature must, of course, fall within the limits set by the available heating and cooling water temperatures. The heating water for the ponds is the condenser cooling water rejected by the NSP power plant. Its temperature varies with time and has been specified by the NWQL as the Mississippi River water temperature at Monticello (Table C-1) plus an increment of 25°F during the summer (April 1 through September 30) and 35°F during the winter (October 1 through March 31). (The lower value corresponds to the operation of two booster pumps in the NSP power plant and the higher value to the operation of a single one.) The cooling water will be pumped from wells which will be drilled near the experimental ponds. The temperature is likely to be fairly constant throughout the year, and 50°F has been chosen as design value, as discussed in part C, section 1.2.

Heating and cooling water temperatures are specified at the locations where they become available: the power plant and the wells, respectively. Pond water temperatures cannot equalthe heating or cooling water temperatures, both because a temperature differential is required to transfer heat and because of losses in the system. These losses cannot be calculated without knowledge of the design of the system. However, preliminary estimates of the temperature differentials can be made. To this end it has been somewhat arbitrarily assumed that there will be a 12°F differential between the water sources and the ponds. The 12°F actually arose from some preliminary trials based on heating a pond from the bottom, but it appears to be a reasonable figure for any heating or cooling configuration. This means that the hottest pond is limited in maximum temperature to 12°F less than the water temperature discharged by the NSP plant and the coldest pond is limited to 12°F warmer than the well water in summer--62°F (50°F + 12°). The 12°F differential will need to be verified after the heat exchange system is finally designed.

When the 12°F differential is applied to the heated water, the maximum available heated pond temperature is 13°F when the plant increment is 25°F (April 1 to September 30) and 23°F when the plant increment is 35°F (October 1 to March 31) over the Mississippi River water temperatures at those times. Based on the mean monthly Mississippi River temperature given in Table C-1 and applying the maximum available heating and cooling water temperatures, the obtainable range of mean monthly pond water temperatures is given in Table D-2 and reproduced in Appendix B-2, Set I.

In order to obtain the highest mean monthly temperatures, heat must be added to the pond, while the coldest pond water temperatures will be obtained by heating in winter (in order to keep the pond ice-free) and cooling in summer.

1.3 Mean Monthly Heat Exchange through a Pond Surface

With the pond temperatures specified above, the mean monthly heat loss through the water surface could be calculated. Input values were mean monthly values of the variables; these have been assembled from the appropriate section of part C in Appendix B-1. Results are shown for the estimated hottest pond in Table D-3 and for the estimated coldest pond in Table D-4. Values for an estimated intermediate pond are in Table D-5. The contributions of the individual heat exchange mechanisms are displayed in the tables. Clearly, precipitation has a negligible effect on mean monthly water temperatures.

Heat loss from a hot pond is mostly by evaporation in mid-summer and is in approximately equal amounts by conduction and evaporation in winter. For the chosen pond water temperatures the need for artificial heating appears to be fairly uniformly distributed over the winter months from October through February. The heating requirements are lowest in April, when only moderately warm pond temperatures can be achieved because of the low heating water temperature.

The coldest pond has to be cooled mainly from April through August with maximum cooling effort required in July. The low cooling requirements for fall and spring should be interpreted in terms of duration of cooling rather than rate, as the extreme-value analysis will show. Cooling is required to compensate essentially for radiation input. Conduction contributes little to the need for cooling.

As pointed out earlier, there is some uncertainty regarding the form of the wind speed function $f(U)$. Fortunately, the range from $U = 9.2$ to 12.3 mph as used in the mean monthly values computation appears to produce the least controversial results (with the exception of Morton's equation), as was shown by Fig. D-1. However, the equations referred to in Fig. D-1 have not usually been derived from mean monthly values of the meteorological data. Also, the wind speed function is only one point of uncertainty, though probably the largest one. Taking data from different sources and different time periods also may introduce errors into the results. It is desirable, therefore, to test the method by which surface heat transfer values were calculated.

Appendix A-1 gives two heat flux values which were obtained independently by the Heat Transfer Laboratory using another method. They refer to a hot pond of 60^{o}F water temperature. The calculated heat fluxes are 4435 BTU ft^{-2} day^{-1} for November and 7362 BTU ft^{-2} day^{-1} for January. The method used herein gives values of 2430 and 4500 BTU ft^{-2} day^{-1}, respectively, for the same meteorological conditions.

The previous computations assume steady conditions. In spring the desired pond water temperatures are increasing (Appendix B-2). Additional heat not shown in Table D-3 is required to bring the ponds to the new temperatures. Similarly, in fall heat will be released from the ponds, and the entire heating requirement shown in Table D-4 will not be needed during this time while the ponds are cooling.

Another test of the method of calculation was made by calculating the mean monthly heat flux for the Mississippi River at Monticello. Mean monthly surface water temperatures and the associated saturation vapor pressures were used as T_s and e_s values, respectively. The resulting net mean monthly heat flux through the water surface is shown in Table D-6. The results relative to each other and the absolute values of the heat fluxes appear to be quite acceptable. The calculated net heat flux is never close to zero except during two months, which means that only two of the river water temperatures listed are equilibrium temperatures. There is a large heat deficit in winter, as there should be, meaning that the equilibrium temperature is below 32°F, or below the freezing point. Indeed, in winter large portions of the Mississippi River are covered by ice. Ice reduces evaporation, heat conduction, and radiation drastically. The calculation method used applies to open bodies of water only. It does not include the tempering effect of an ice cover on heat losses. Therefore the finding of large negative heat fluxes in mid-winter is well justified. The results correspond to a situation in which the ice cover is always artificially removed. The values shown for midwinter in Table D-6 are in fact the approximate mean amounts of heat which would be required to keep the Mississippi River free of ice.

Early in spring, river water temperatures are increasing, but apparently not as fast as the solar radiation would indicate. The reason is that at that time of the year the river receives much runoff from snowmelt, part of it through the ground. Much heat is required to melt the snow and to raise the temperature of the water and the soil before an equilibrium state is reached. The river water temperatures naturally lag behind. It is not a coincidence that the maximum runoff in the Mississippi River and the mean maximum net heat input occur simultaneously in April.

In July and August the river flow is usually low, and therefore the heat demand is low as well. As the river water temperature decreases, no heat addition is needed, and an equilibrium is reached in the fall.

It can be concluded that the computational method used to compute mean monthly heat transfer values furnishes values of the right order of magnitude for every month. However, it is still difficult to pinpoint the accuracy of the method.

1.4 Extreme Monthly Heat Exchange through a Pond Surface

The design of heat exchange facilities cannot be based on mean monthly surface heat loss values alone. Some idea must also be had of the range of heat flux values across the water surface, and such information appears quite difficult to obtain. If the basic equations apply with input parameters of any magnitude, as ideally they should, it should be possible to choose input values having various probabilities of occurrence and to find the joint probabilities of the results. Unfortunately, since meteorological parameters such as air temperature, wind velocity, and relative humidity are not statistically independent, it is not possible to follow the above procedure. Therefore another procedure was adopted which was founded on the availability of data giving systematic simultaneous readings of meteorological data over a long period of time. Reference [20] analyzes hourly readings of temperature, wind speed, and relative humidity occurrences in tabular form for Minneapolis for each month over a ten-year period. Hourly readings are sorted into four ranges of wind speeds (0-4, 5-14, 15-24, and over 25 mph), six ranges of relative humidity (under 30, 30-39, 40-49, 50-69, 70-79, 80-89, and 90-100 per cent), and air temperature intervals of five degrees (e.g., 44/40, 39/35, 34/30). The number of hourly readings in the ten-year period falling under any combination of these ranges is given in Ref. [20].

With this information the heat flux through the water surface for any one combination of these categories could be calculated. Actually, only the partial heat flux which depends on these three parameters was calculated. This consists of the sum of atmospheric radiation, backradiation, conduction, and evaporation--or, using the symbols of Eq. (B-1), $H_a + H_{br} + H_c + H_e$. The calculation was made on an hourly basis for each combination of the parameters using the mid-range value for each parameter, and histographic tables were constructed showing the number of hours during which a specific range of partial heat fluxes existed. As an example, the partial heat flux histogram for January with a pond water temperature of 56°F is given in Table D-7.

The mean of the distribution is given at the end of the table, as are the standard deviation and skewness (the distribution is so slightly skewed that the dimensionless skewness coefficient is only 0.00009). For comparison, it may be noted that the mean monthly meteorological data for January from Table D-3 produce a partial heat flux $H_a + H_{br} + H_e + H_c = 2518 - 3578 - 1465 - 1814 = -4339$ BTU ft^{-2} day^{-1}. The results differ by 550 BTU ft^{-2} day^{-1}, which does not appear unreasonable. (Nine hours of readings were missing from the records, and therefore the total number of hours is 7431 instead of 7440 in Table D-7.)

In conference with members of the NWQL it was decided to retain for analysis the heat flux values in the range from 15 to 85 per cent probability of occurrence for design purposes, with 15 per cent representing 108 hours in a month of 30 days. In Table D-7, these fall in the -5500 to -5000 and -3000 to -2500 BTU ft^{-2} day^{-1} ranges, respectively. (The 108 hours of extremely high or low heat flux cannot reasonably occur consecutively; nor are they likely to be randomly distributed on an hourly basis, because hourly values of meteorological conditions are correlated for short time lags, say 12 to 36 hours. The effects on pond water temperatures of extreme conditions lasting various lengths of time will be discussed in section 2.7, following.)

Using the 15 and 85 per cent frequency limits for design heat flux with the pond water temperatures given in Appendix B-2, Set I and the data from Ref. [20] produced the heat flux requirements shown in Table D-8. The net heat flux defined by Eq. (B-1) must include solar radiation and precipitation in addition to the partial heat fluxes given in Table D-8. This means that the contributions of the terms H_s and H_p in Eq. (B-1) must be evaluated. It is quite likely that solar radiation, air temperature, and relative humidity are correlated variables. However, this relationship could not be put into quantitative form, and thus the uncorrelated value for H_s was taken from column (1) of Appendix B-1 or from Table C-2.

With high solar radiation, air temperatures are also likely to be high. As a consequence, heat losses from the pond will probably not be at their maximum. Similarly, small solar radiation will probably be associated with large heat loss values from a pond. Therefore, low values of solar radiation from Table C-2 were added to large values of heat loss through the water surface from Table D-8 and large radiation losses to small heat losses to obtain the net heat flux values; these are given in Table D-9. (The values in Table C-2 need to be multiplied by 3.685 BTU ft^{-2} $Langley^{-1}$ before addition. The values are also rounded off to the nearest one hundred BTU ft^{-2} day^{-1}.)

The addition of two values of identical probability of exceedence does not give a result with the same probability. The relative magnitude of the two values and the degree of correlation have to be considered. Since the latter is unknown, however, as regards H_s and the other parameters, the results arrived at in Table D-9 represent rough values of an estimated probability of exceedence.

The amount of heat added to or withdrawn from a pond by precipitation is shown in Table D-10 for typical pond temperatures T_s given in Appendix B-2, precipitation temperatures T_p, and precipitation intensities I.

Table C-7 shows that precipitation of 1.0 in.day is a relatively rare event. The chance of its occurrence is less than 5.3 per cent of 52.1 days with precipitation. On the average only 2.5 days in every year will see precipitation over one inch. The event is likely to occur when neither solar radiation nor evaporation is at its extreme. Therefore, as a rough estimate, a heat flux of $H_p = - 200$ BTU ft^{-2} day^{-1} will be considered for precipitation during April through October. This value will be added to the heating requirement, but will not be subtracted from the cooling requirement.

Extreme snowfall conditions were shown in Fig. C-13. These are likely to be associated with high winds and low solar radiation. A maximum daily value with a 50 per cent probability of exceedence, which means that this event would on the average occur on one day in every second year, has a water equivalent of 0.5 inches. Table D-10 shows that this value corresponds roughly to a heat loss of $H_p = -500$ BTU ft^{-2} day^{-1} to be used for the months of November through March.

1.5 Total Surface Heat Exchange

Examination of Table D-9 shows that the months of July and November present critical conditions for the coldest and hottest ponds, respectively. To maintain 63°F in November in the hottest pond the additional amount of heat required is $- 5800 - 500 = - 6300$ BTU $ft^{-2} day^{-1}$. To maintain 62°F in July in the coldest pond, + 5700 BTU ft^{-2} day^{-1} must be removed from the pond. The table also shows that heating and cooling may be required in some ponds the year around.

At this point it would be useful to compare the monthly extreme values from section 1.4 with the monthly mean values from section 1.3. The comparison is made in Table D-11. The table shows that the heating capacity will be fairly well used. With the exception of three months (April through June), the monthly extremes are between 1.6 and 2.2 times the mean monthly heating requirements. The mean and extreme monthly cooling requirements are not as well balanced. The test ratio for cooling is 2.3. From September through March the cooling capacity will rarely be used.

In accordance with standard engineering practice the facilities should be designed with some margin of safety. However, if for reasons of economy no margin is provided, the temperatures in Appendix B-2, Set I may be maintained with heat exchangers designed for a heating capacity of 6300 BTU ft^{-2} day^{-1} and a cooling capacity of 5700 BTU ft^{-2} day^{-1}.

Although the previous computations allow for monthly variations in heating water temperature, they do not consider shorter period fluctuations. It has been assumed that a 12°F temperature differential between heating water and pond water always exists. Because of the fluctuations in Mississippi River water temperature and the constant temperature rise through the power plant, this is not realistic. Low heating water temperatures are very likely to coincide with large heating requirements because of the fast response of Mississippi River temperatures near Monticello to meteorological conditions. Spring and fall will see the strongest water temperature changes. Table D-11 shows that spring heating requirements are less than those in fall. Hence, the strongest excursions of pond water temperatures from their nominal values in Appendix B-2, Set I must be expected in fall. If lower nominal values for the hottest pond are established, the problem will not arise. A lowering of the September, October, and November temperatures by 5°F below the values shown in Appendix B-2, Set I for the hottest pond would eliminate the excursions in pond temperature. A decision to lower maximum pond temperature can be treated as a matter of pond operation rather than one of design. Another alternative would be to use an emergency heating system. This would be necessary in any event, because the power plant providing the heating water will be shut down for several weeks a near for refueling, maintenance, etc. The emergency heating system could be used to raise heating water temperatures when required to eliminate pond temperature excursions.

The previously given design values of heating and cooling capacities result from the assumed pond water temperatures shown in Appendix B-2, Set I. If the winter temperatures of the hottest pond can be lowered below those shown without jeopardizing the purpose of the contemplated experiments on aquatic life, the design value for heating can be reduced. To examine the possibilities of such reduced pond temperatures, a modified set of pond water temperatures for the hottest ponds is proposed and is given in Appendix B-2, Set II. In this set the minimum hot water pond temperature is still maintained 15°F above freezing as compared to 24°F above freezing in the original set. Summer temperatures have not been altered, because 89°F is already a low figure for studies on thermal effects.

By following the same procedures as outlined before, the heat flux values displayed in Table D-12 were obtained from the Set II pond temperatures. None of the extreme values in Table D-12 exceeds a requirement of 4800 BTU ft^{-2} day^{-1} for either heating or cooling.

The main features of a heat exchanger system for this value are presented in section F. This is not conservative design, but rather is aimed at the smallest possible installation which will provide temperature control within the most economical limits. The figures given are low for several reasons: The Meyer equation gives rather low evaporative heat flux values under extreme conditions as compared to other equations; 15 per cent probability of exceedence is not a very extreme figure; no design margin has been allowed; and the available heating water temperatures will fluctuate strongly with Mississippi River water temperatures. Thus excursions of pond water temperatures from their nominal values must certainly be expected. The order of magnitude of these anticipated excursions will be discussed in section 3, below. If such excursions can be tolerated, the minimum design conditions proposed herein would provide great economy. In any event, a more powerful heating system with more conservative design heat flux values can be developed without difficulty if this appears desirable.

2. Heat Flow through the Ground

Heat is transferred to the ground both through seepage and through conduction. Seepage water goes into the groundwater table, which is assumed to be at some unknown distance below the bottom of the pond. A seepage rate of 0.5 in.-day^{-1} appears reasonable according to arguments presented in part E, following. The make-up water for the seepage loss is likely to be ground water. When it reaches the pond its temperature will be different from that of the pond, but by no more than 25°F. This represents a maximum heat flux differential of ± 65 BTU ft^{-2} day^{-1}, which is less than two per cent of the maximum design value and can be neglected.

Heat conduction through the pond can be studied in an approximate manner by considering a two-dimensional flow net which represents a crosssectional view through the pond. A steady state condition is assumed. Two cases have been investigated: one with the groundwater table a short distance below the bottom of the pond and one with the groundwater table at a great depth. When ground water is present it acts as a heat sink. The groundwater temperature is assumed to be constant at 50°F. In the absence of a groundwater table all heat is carried back to the surface of the ground. The surface temperature of the ground is assumed to be that of the air. The largest temperature difference between nominal water temperatures given in Appendix B-2 and mean monthly air temperatures given in column (2) of Appendix B-1 occurs in January, and conditions for that month have been studied.

The approximate two-dimensional flow nets for a case with ground water and one without it are shown in Fig. D-2. It has been assumed that the soil is homogeneous with a uniform thermal conductivity.

The upper flow net, referring to the case with ground water close to the surface, shows that the heat flux through the vertical wall is transmitted to the surface of the soil, while the heat flux through the bottom is mostly transmitted to the ground water. The heat flux through the vertical wall resembles that of a vortex flow. The heat flux for such a flow is

$$q_{vortex} = - k_{soil} \frac{(T_s - T_a)}{\alpha} \ln \frac{R}{r_o} \qquad \text{(D-4)}$$

In this equation the thermal conductivity of the soil $k_{soil} = 1.5$ BTU hr^{-1} ft^{-1} $^oF^{-1}$, the temperature differential between water and air $T_s - T_a = 46^oF$, and the angle between the vertical wall of the pond and the sloping surface of the ground $\alpha \approx \frac{5\pi}{8}$. The outer radius of the flow field is equal to the height of the wall, $R = 6$ ft. The inner radius has been chosen as $r_o = 0.5$ inches. The heat flux per unit length of contour is then

$$q_{wall} \approx q_{vortex} = - 1.5 \times 46 \times \frac{8}{5\pi} \times \ln 144 = - 175 \text{ BTU } hr^{-1} \ ft^{-1}$$

This value is approximate and represents the situation on one side of the pond. On the other three sides the heat fluxes will be of a comparable order of magnitude.

The conductive heat flux from the pond to the ground water is approximately

$$H_{bottom} = - k_{soil} \frac{T_s - T_{ground}}{d} \qquad \text{(D-5)}$$

With a temperature differential $T_s - T_{ground} = 6°F$ and an average distance $d = 4$ ft between the bottom of the pond and the aquifer, the partial heat flux becomes

$$H_{bottom} = - 1.5 \times \frac{6}{4} = 2.25 \text{ BTU hr}^{-1} \text{ ft}^{-2}$$

The total conductive heat loss through the soil for the situation shown in the upper sketch of Fig. D-2, referred to a unit surface area of the pond, will be approximately

$$H_{c,soil} = \frac{q_{wall}\, C}{A_s} + H_{bottom} \qquad \text{(D-6)}$$

Where the length of the contour of the pond $C = 445.2$ ft and the surface area $A_s = 10,900$ ft^2,

$$H_{c,soil} = - \left[\frac{175 \times 445.2}{10,900} + 2.25\right] \times 24 = - (7.15 + 2.25)24 =$$

$$- 226 \text{ BTU ft}^{-2} \text{ day}^{-1}$$

It can be seen that most of the loss occurs through the walls rather than the bottom.

The total heat flow through the ground, including conduction and seepage, thus is probably less than 226 + 65 = 291 BTU ft^{-2} day^{-1}, which is about 6 per cent of the reduced design heat flux value.

The flow net in the lower sketch of Fig. D-2 deals with the case in which the water table is absent. The flow net results in an approximate heat flow rate of 47 BTU hr^{-1} ft^{-1} length of contour, which is much less than for the situation sketched in the upper part of Fig. D-2.

The previous computations assume steady state (time-independent) conditions. In reality, heat flow through the ground will be mostly under unsteady conditions. In spring, when the nominal pond water temperatures increase, the soil will also have to be warmed. Figure D-2 shows that the volume of soil involved is small, however, and therefore no significant amounts of heat will be required in this case.

If the pond water temperatures are less than 50°F, heat will actually be supplied from the ground water to the pond through the bottom. This benefit will be valuable in winter, though the amount of heating will again be quite small.

3. Temperature Response of Ponds

It is desirable to determine what pond water temperatures will be obtained when the heat exchanger cannot provide or remove sufficient heat or when it fails completely. The unsteady temperature regime of the ponds must be studied for this information. The experimental ponds will be well-mixed bodies of water, each with a quarter acre of surface area (10,900 sq ft) and an average depth of 5.9 ft. The volume of one pond is close to 64,000 cu ft.

The rate of temperature change of a pond with time is proportional to the total rate of heat addition or withdrawal; that is,

$$\frac{dT_s}{dt} = \frac{H}{c_p \rho h} \qquad \text{(D-7)}$$

where c_p is the specific heat, ρ the density of water, h the average depth of the pond, and H the heat flux per unit surface area at a given time. Thus, the temperature drop per unit time is proportional to the heat flux at that particular time. In finite difference form, Eq. (D-7) is

$$\Delta T_s = H \times \frac{\Delta t}{c_p \rho h} \qquad \text{(D-8)}$$

Taking a time interval Δt of one hour,

$$\Delta T_s(^\circ F) = H(\text{BTU ft}^{-2}\text{ day}^{-1}) \times 1.13 \times 10^{-4}(^\circ F\text{ BTU}^{-1}\text{ ft}^2\text{ day}) \qquad \text{(D-9)}$$

For every one thousand BTU ft^{-2} day^{-1} heat flux, the temperature change is 0.11°F per hour.

As the pond water temperature changes, the rate of surface heat transfer H changes as well. The effect of this decrease is that the temperature follows an exponential law if the meteorological conditions remain unchanged. In this case, if the pond temperature is $T_s(0)$ at time $t = 0$, the water temperature will change according to the relationship

$$T_s(t) = E(0) + [T_s(0) - E(0)]e^{-mt} \tag{D-10}$$

where

$$m^{-1} = \frac{c_p \rho h}{K(0)} \tag{D-11}$$

is the time constant. Its value for $h = 6$ ft and $K = 150$ BTU ft^{-2} day^{-1} $°F^{-1}$ is approximately 59 hours. A time constant of 38.5 hours and a half-time response of 26 hours have been calculated and are also given in Appendix A-1. Appendix A-2 shows the effect of wind and humidity on the half time. The half time measures the speed with which a pond responds to changes in meteorological conditions.

From Eq. (D-11), using Eq. (C-2), the temperature change from the nominal pond water temperature can be derived in the form

$$T_s(t) - T_s(0) = \frac{H(0)}{K(0)} (1 - e^{-mt}) \tag{D-12}$$

The first term on the right-hand side depends on the rate of surface heat flux at time zero. The second term is a dimensionless decay function which needs to be evaluated only once if the surface heat transfer coefficient K(0), and hence m, is fixed. Table D-13 gives numerical values for the decay function for $K = 150$ BTU ft^{-2} day^{-1} $°F^{-1}$. Actually, the temperature change does not depend a great deal on the surface heat exchange coefficient K. To illustrate this, the term $\frac{1}{K}(1 - e^{-mt})$ has been evaluated for various K values in Table D-14. Wind will have a particularly strong influence on the temperature decay because of its effect on heat flux, while humidity will be less significant. This is illustrated by the graphs in Appendix A-2.

To show the significance of the above relationships, particularly Eqs. (D-9) and (D-12), several specific cases will be examined:

a. Temperature decay in pond under severe winter conditions. The design value of the heat exchange is, for reasons of economy, less than the extreme heating requirements. Assuming that the heat exchanger provides 4800 BTU ft^{-2} day^{-1}, any deficit beyond this value will result in a water temperature drop. For the purpose of illustration taking the worst possible figures from Table D-7 in the worst consecutive order, the temperature drop in the pond from the initial value of 56°F can be calculated as shown in Table D-15.

If the heating system failed completely in this situation, an additional temperature drop of 0.54°F would occur in every hour. The final temperature after 12 hours would be 5.71 + (12 x 0.54) = 12.27°F below the nominal 56°F temperature. The largest heat losses will generally occur during the night. The case illustrated by the figures in Table D-15 can be looked upon as a rather severe situation on a January night. Diurnal water temperature fluctuations in the pond should usually be less severe than those illustrated by this example, but a very few may be worse.

b. If the heating system failed under mean January conditions (Table D-3), with $H = 3723$ BTU ft^{-2} day^{-1} and $K = 150$ BTU ft^{-2} day^{-1}, the temperature decay, according to Eq. (D-12) and Table D-13, would be as shown in Table D-16. At this point it should be mentioned that the well water can be used in mid-winter to avoid freezing of the ponds. With well water of 50°F it will be possible to keep the ponds ice-free so long as a sufficient flow rate is provided. For that purpose 2.0 cfs of well water for eight ponds appears to be a lower limit. More detailed computations can be made if this solution is adopted.

c. A third case of interest is the response of the pond to a snow storm. Assume a snow storm occurs producing 0.5 inches of water equivalent in one hour. This represents an approximate heat requirement of 500 BTU ft^{-2} hr^{-1} or 12,000 BTU ft^{-2} day^{-1}. If it is assumed that no additional heating capacity is available, a temperature drop of 1.4°F will be produced by the snow storm.

As the pond water changes in the unsteady regime it always tends toward the equilibrium temperature. Equilibrium temperatures vary widely as meteorological conditions change. To illustrate this point, the equilibrium temperatures required to produce the low and high surface heat flux values shown in Table D-11 for the month of November can be calculated using Eq. (C-2) in the form $E = T_s + H/K$. With a K value of 150 BTU ft^{-2} day^{-1} $^{o}\mathrm{F}^{-1}$ the results are

For unfavorable weather conditions: $$E = 63 - \frac{6300}{150} = 21^{o}\mathrm{F}$$

For favorable weather conditions: $$E = 40 + \frac{2400}{150} = 56^{o}\mathrm{F}$$

The mean value of these extremes is 38.5°F. The mean monthly equilibrium temperatures calculated to produce the mean monthly heat fluxes in Tables D-3 and D-4 are

$$E = 63 - \frac{3410}{150} = 40.2$$

$$E = 40 - \frac{568}{150} = 36.2$$

with a mean of 38.2°F. The measured Mississippi River water temperature for November is 40°F, and this should be near the equilibrium temperature for the month. All these values are in fairly reasonable agreement. The wide range of equilibrium temperatures points to the fact that the rapidity with which the pond water temperature will change in case of a failure of the total heat control system or of insufficient heat input or withdrawal depends strongly on the meteorological conditions at the particular time.

Table D-1

WIND SPEED FUNCTION COEFFICIENTS (from [17])

Source	a	b	c
Meyer	73	7.3	0
Brady, et al.	70	0	0.70
Morton	85	14.0	0
Lake Hefner	0	11.4	0
Lake Colorado City	0	16.8	0

Table D-2 (also APPENDIX B-2)

ESTIMATED MEAN MONTHLY POND TEMPERATURES IN ^{o}F

SET I

Month	Hottest	Coldest
Jan	56	32 (Heated)
Feb	56	32 (Heated)
Mar	58	35 (Natural)
Apr	57	44 (Natural)
May	72	59 (Natural)
June	81	62 (Cooled)
July	89	62 (Cooled)
Aug	86	62 (Cooled)
Sept	78	62 (Cooled)
Oct	75	52 (Natural)
Nov	63	40 (Natural)
Dec	57	34 (Natural)

TABLE D-3 - MEAN MONTHLY HEATLOSS THROUGH THE WATERSURFACE FOR NORMAL METEOROLOGICAL CONDITIONS

HOTTEST POND

	TS	ES	HS	HA	HBR	HE	HC	XLOSS	HPR	HN
	°F	IN HG			BTU PER SQUAREFOOT PER DAY					
Jan	56	.452	638	2518	-3578	-1465	-1814	-6857	-22.2	-37[illegible]
Feb	56	.452	991	2585	-3578	-1454	-1708	-6740	-24.5	-31[illegible]
Mar	58	.486	1314	2845	-3630	-1439	-1318	-6387	-38.4	-2267
Apr	57	.469	1589	3244	-3604	-1135	-604	-5343	-5.0	-524
May	72	.792	1815	3567	-4016	-1948	-664	-6628	-10.0	-1256
June	81	1.068	1984	3825	-4279	-2372	-625	-7275	-12.3	-1478
July	89	1.379	2079	3987	-4524	-3078	-660	-8263	-10.2	-2207
Aug	86	1.254	1840	3919	-4431	-2790	-645	-7866	-11.2	-2118
Sept	78	.968	1254	3652	-4190	-2201	-741	-7132	-8.0	-2235
Oct	75	.876	887	3355	-4102	-2477	-1111	-7689	-7.9	-3455
Nov	63	.580	542	2932	-3765	-1722	-1356	-6843	-40.6	-3410
Dec	57	.469	450	2651	-3604	-1460	-1605	-6669	-22.3	-3590

TABLE D-4 .. MEAN MONTHLY HEATLOSS THROUGH THE WATERSURFACE FOR NORMAL METEOROLOGICAL CONDITIONS

COLDEST POND

	TS	ES	HS	HA	HBR	HE	HC	XLOSS	HPR	HV
	°F	IN HG			BTU PER SQUAREFOOT PER DAY					
Jan	32	.180	638	2518	-2989	-411	-866	-4265	-19.2	-1128
Feb	32	.180	991	2585	-2989	-385	-746	-4120	-21.2	-565
Mar	35	.203	1314	2845	-3058	-311	-382	-3751	-33.3	374
Apr	44	.289	1580	3244	-3273	-384	-51	-3708	-1.4	1115
May	59	.504	1815	3567	-3657	-806	-138	-4600	-2.1	780
June	62	.560	1984	3825	-3737	-403	126	-4014	2.5	1798
July	62	.560	2079	3987	-3737	-133	330	-3540	5.1	2530
Aug	62	.560	1840	3919	-3737	-269	245	-3762	4.3	2002
Sept	62	.560	1254	3652	-3737	-658	-123	-4519	-1.3	385
Oct	52	.390	887	3355	-3474	-566	-188	-4228	-1.3	12
Nov	40	.248	542	2932	-3176	-405	-425	-4006	-35.3	-568
Dec	34	.195	450	2651	-3035	-393	-691	-4119	-19.4	-1038

TABLE D-5 - MEAN MONTHLY HEATLOSS THROUGH THE WATERSURFACE
FOR NORMAL METEOROLOGICAL CONDITIONS

INTERMEDIATE POND

	TS	FS	HS	HA	HBR	HE	HC	XLOSS	HPR	HN
	°F	IN HG	BTU PER SQUAREFOOT PER DAY							
Jan	47	.324	638	2518	-3347	-969	-1459	-5775	-21.1	-2640
Feb	47	.324	991	2585	-3347	-951	-1347	-5646	-23.2	-2094
Mar	49	.349	1314	2845	-3398	-893	-952	-5242	-36.4	-1120
Apr	60	.522	1580	3244	-3684	-1356	-732	-5772	-6.0	-954
May	69	.715	1815	3567	-3931	-1643	-542	-6116	-8.2	-742
June	77	.936	1984	3825	-4161	-1860	-466	-6487	-9.2	-687
July	81	1.068	2079	3987	-4279	-1960	-367	-6606	-5.7	-546
Aug	77	.936	1840	3919	-4161	-1635	-311	-6107	-5.4	-353
Sept	69	.715	1254	3652	-3931	-1244	-394	-5569	-4.3	-667
Oct	63	.580	887	3355	-3765	-1313	-630	-5707	-4.5	-1469
Nov	57	.469	542	2932	-3604	-1292	-1113	-5999	-39.2	-2564
Dec	50	.363	450	2651	-3423	-1047	-1327	-5797	-21.4	-2717

TABLE D-6 - MEAN MONTHLY HEATLOSS THROUGH THE WATERSURFACE FOR NORMAL METEOROLOGICAL CONDITIONS

MISSISSIPPI RIVER

	TS	ES	HS	HA	HBR	HE	HC	XLOSS	HPR	HV
	°F	IN HG	BTU PER SQUAREFOOT PER DAY							
Jan	33	.188	638	2518	-3012	-442	-905	-4359	-19.4	-1222
Feb	33	.168	991	2585	-3012	-417	-786	-4214	-21.3	-560
Mar	35	.203	1314	2845	-3058	-311	-382	-3751	-33.3	374
Apr	44	.289	1580	3244	-3273	-384	-51	-3708	-.4	1115
May	59	.504	1815	3567	-3657	-806	-138	-4600	-2.1	780
June	68	.691	1964	3825	-3903	-911	-111	-4924	-2.2	883
July	76	.906	2079	3987	-4131	-1377	-183	-5692	-2.8	371
Aug	73	.819	1840	3919	-4044	-1210	-163	-5417	-2.8	339
Sept	65	.623	1254	3652	-3819	-896	-239	-4955	-2.6	-52
Oct	52	.390	887	3355	-3474	-566	-188	-4228	-1.3	12
Nov	40	.248	542	2932	-3176	-405	-425	-4006	-35.3	-568
Dec	34	.195	450	2651	-3035	-393	-691	-4119	-19.4	-1038

[illegible] CALCULATED PARTIAL HEAT FLUX FOR
JANUARY .THE POND WATERTEMPERATURE IS 56° F.

HEAT FLUX RANGE IN BTU PER SQUARE FOOT PER DAY			TOTAL NUMBER OF HOURS IN 10 YEARS	FREQUENCY IN PERCENT	CUMULATIVE FREQUENCY IN PERCENT
-18000	TO	-17500	0	0.0	0.0
-17500	TO	-17000	0	0.0	0.0
-17000	TO	-16500	0	0.0	0.0
-16500	TO	-16000	0	0.0	0.0
-16000	TO	-15500	0	0.0	0.0
-15500	TO	-15000	0	0.0	0.0
-15000	TO	-14500	0	0.0	0.0
-14500	TO	-14000	0	0.0	0.0
-14000	TO	-13500	0	0.0	0.0
-13500	TO	-13000	0	0.0	0.0
-13000	TO	-12500	0	0.0	0.0
-12500	TO	-12000	0	0.0	0.0
-12000	TO	-11500	0	0.0	0.0
-11500	TO	-11000	0	0.0	0.0
-11000	TO	-10500	1	.0	.0
-10500	TO	-10000	0	0.0	.0
-10000	TO	-9500	1	.0	.0
-9500	TO	-9000	4	.1	.1
-9000	TO	-8500	2	.0	.1
-8500	TO	-8000	20	.3	.4
-8000	TO	-7500	27	.4	.7
-7500	TO	-7000	59	.8	1.5
-7000	TO	-6500	113	1.5	3.1
-6500	TO	-6000	175	2.4	5.4
-6000	TO	-5500	321	4.3	9.7
-5500	TO	-5000	488	6.6	16.3
-5000	TO	-4500	580	7.8	24.1
-4500	TO	-4000	1180	15.9	40.0
-4000	TO	-3500	916	12.3	52.3
-3500	TO	-3000	1630	21.9	74.2
-3000	TO	-2500	912	12.3	86.5
-2500	TO	-2000	578	7.8	94.3
-2000	TO	-1500	351	4.7	99.0
-1500	TO	-1000	71	1.0	100.0
-1000	TO	-500	2	.0	100.0
-500	TO	0	0	0.0	100.0
0	TO	500	0	0.0	100.0
500	TO	1000	0	0.0	100.0
1000	TO	1500	0	0.0	100.0
1500	TO	2000	0	0.0	100.0
2000	TO	2500	0	0.0	100.0
2500	TO	3000	0	0.0	100.0
3000	TO	3500	0	0.0	100.0
3500	TO	4000	0	0.0	100.0
4000	TO	4500	0	0.0	100.0
4500	TO	5000	0	0.0	100.0
5000	TO	5500	0	0.0	100.0
5500	TO	6000	0	0.0	100.0
6000	TO	6500	0	0.0	100.0
6500	TO	7000	0	0.0	100.0

MEAN VALUE -3759.09
STANDARD DEVIATION 1252.61
SKEWNESS -.00

Table D-8

PARTIAL SURFACE HEAT FLUX VALUES

$H_a + H_{br} + H_c + H_e$ in BTU ft^{-2} day^{-1}

Month	Hottest Pond		Coldest Pond	
	Probabilities of Exceedence in Per Cent			
	85	15	85	15
Jan	-5500	-2500	-3000	+ 500
Feb	-6000	-2000	-2500	+1000
Mar	-5000	-1500	-2000	+1500
Apr	-3500	- 500	-1500	+2000
May	-5000	- 500	-2500	+1500
June	-5000	-1500	-1500	+2000
July	-6000	-2000	- 500	+3000
Aug	-5500	-1500	-1000	+2500
Sept	-5500	-1000	-2500	+1500
Oct	-6000	-1500	-2000	+1500
Nov	-6000	-1500	-2500	+1500
Dec	-5500	-1500	-2500	+ 500

Table D-9

PARTIAL SURFACE HEAT FLUX VALUES WITH SOLAR RADIATION

$H_s + H_a + H_{br} + H_c + H_e$ in BTU ft^{-2} day^{-1}

Month	Hottest Pond		Coldest Pond	
	Probabilities of Exceedence in Per Cent (Approx.)			
	85	15	85	15
Jan	-5100	-1500	-2600	+1500
Feb	-5400	- 700	-1900	+2300
Mar	-4300	+ 300	-1300	+3300
Apr	-2800	+1800	- 800	+4300
May	-4100	+2100	-1600	+4100
June	-3900	+1200	- 400	+4700
July	-4600	+ 700	+ 900	+5700
Aug	-4300	+ 900	+ 200	+4900
Sept	-5000	+ 900	-2000	+3400
Oct	-5600	- 200	-1600	+2800
Nov	-5800	- 600	-2300	+2400
Dec	-5300	- 800	-2300	+1200

Table D-10

HEAT ADVECTED BY PRECIPITATION H_p in BTU ft^{-2} day^{-1} for 1.0 in ft^{-2} day^{-1} OF PRECIPITATION INTENSITY

Summer (Eq. B-7)

T_p (°F)	T_s (°F)		
	40	70	90
90	259	104	0
80	208	52	- 52
70	156	0	-104
60	104	- 52	-156
50	52	-104	-208
40	0	-156	-259

Winter (Eq. B-8)

T_p (°F)	T_s (°F)		
	40	70	90
-30	-940	-1124	-1228
-20	-912	-1070	-1064
-10	-890	-1040	-1044
0	-866	-1020	-1024

Table D-11

COMPARISON OF MONTHLY MEANS AND EXTREMES OF NET SURFACE HEAT FLUX (INCLUDING PRECIPITATION) FOR HOTTEST AND COLDEST POND in BTU ft^{-2} day^{-1} POND TEMPERATURES OF APPENDIX B-2, Set I

	Hottest Pond			Coldest Pond		
Month	Mean	Low*	Ratio	Mean	High**	Ratio
Jan	-3723	-5600	1.5	-1128	+1500	
Feb	-3189	-5900	1.8	- 565	+2300	
Mar	-2267	-4800	2.1	+ 374	+3300	8.8
Apr	- 524	-3000	5.7	+1115	+4300	3.9
May	-1256	-4300	3.4	+ 780	+4100	5.3
June	-1478	-4100	2.7	+1798	+4700	2.6
July	-2207	-4800	2.2	+2530	+5700	2.3
Aug	-2118	-4500	2.1	+2002	+4900	2.4
Sept	-2235	-5200	2.2	+ 385	+3400	8.8
Oct	-3455	-5800	1.7	+ 12	+2800	
Nov	-3410	-6300	1.8	- 568	+2400	
Dec	-3590	-5800	1.6	-1038	+1200	

*Approx. 85 per cent probability of exceedence

**Approx. 15 per cent probability of exceedence

Table D-12

COMPARISON OF MONTHLY MEANS AND EXTREMES OF NET SURFACE HEAT FLUX (INCLUDING PRECIPITATION) FOR HOTTEST AND COLDEST POND in BTU ft^{-2} day^{-1}--SET II

	Hottest Pond			Coldest Pond		
Month	Mean	Low	Ratio	Mean	High	Ratio
Jan	-2640	-4110	1.5	-1128	+ 970	--
Feb	-2560	-4440	1.7	- 565	+1840	--
Mar	-2267	-4700	2.1	178	+2340	13.1
Apr	- 524	-3000	5.7	884	+3780	4.3
May	-1256	-4300	3.4	641	+3610	5.6
June	-1478	-4100	2.8	1504	+4220	2.8
July	-2207	-4800	2.2	1819	+4720	2.6
Aug	-2118	-4500	2.1	1723	+4440	2.6
Sept	-1863	-4170	2.2	385	+2900	7.5
Oct	-2246	-3830	1.7	- 367	+2340	--
Nov	-2169	-4310	2.0	- 881	+1420	--
Dec	-2598	-4330	1.7	-1325	+ 660	--

Table D-13

DIMENSIONLESS TEMPERATURE CHANGE IN POND

t(hours)	0	1	2	3	4	6	12	24	48
$1 - e^{-mt}$	0	.017	.033	.050	.066	.097	.186	.335	.558

Table D-14

FUNCTION $(1 - e^{-mt}) K^{-1} \times 10^4$

K BTU ft^{-2} day^{-1} $^{o}F^{-1}$ \ t (hrs)	1	2	3	6	12	24	48
50	1.13	2.24	3.37	6.65	13.14	25.42	47.60
75	1.125	2.24	3.35	6.63	12.92	24.55	46.34
100	1.123	2.23	3.34	6.55	12.68	23.75	41.84
150	1.123	2.23	3.32	6.46	12.30	22.33	37.20

Table D-15

CASE STUDY OF TEMPERATURE DECAY FROM 56°F FOR INSUFFICIENT HEATING IN JANUARY

Hour	Heat Deficit, 4800 BTU $ft^{-2} day^{-1}$ applied to Table D-7 Requirements, BTU ft^{-2} day^{-1}	Hourly Temp. Drop (°F)	Temp. Difference from Nominal (°F)
0			
1	5950	.67	-0.67
2	4950	.56	-1.23
3	4450	.50	-1.73
4	4450	.50	-2.23
5	4450	.50	-2.73
6	4450	.50	-3.33
7	3950	.45	-3.78
8	3950	.45	-4.23
9	3450	.39	-4.62
10	3450	.39	-5.01
11	3450	.39	-5.40
12	3450	.39	-5.79

Table D-16

CASE STUDY OF MEAN TEMPERATURE DECAY WHEN HEATING SYSTEM FAILS IN JANUARY AT AN INITIAL POND TEMPERATURE OF 56°F

Hour	0	1	2	6	12	24	48
Temp. Difference from Nominal (°F)	0	-.42	-.84	-2.4	-4.6	-8.3	-13.9

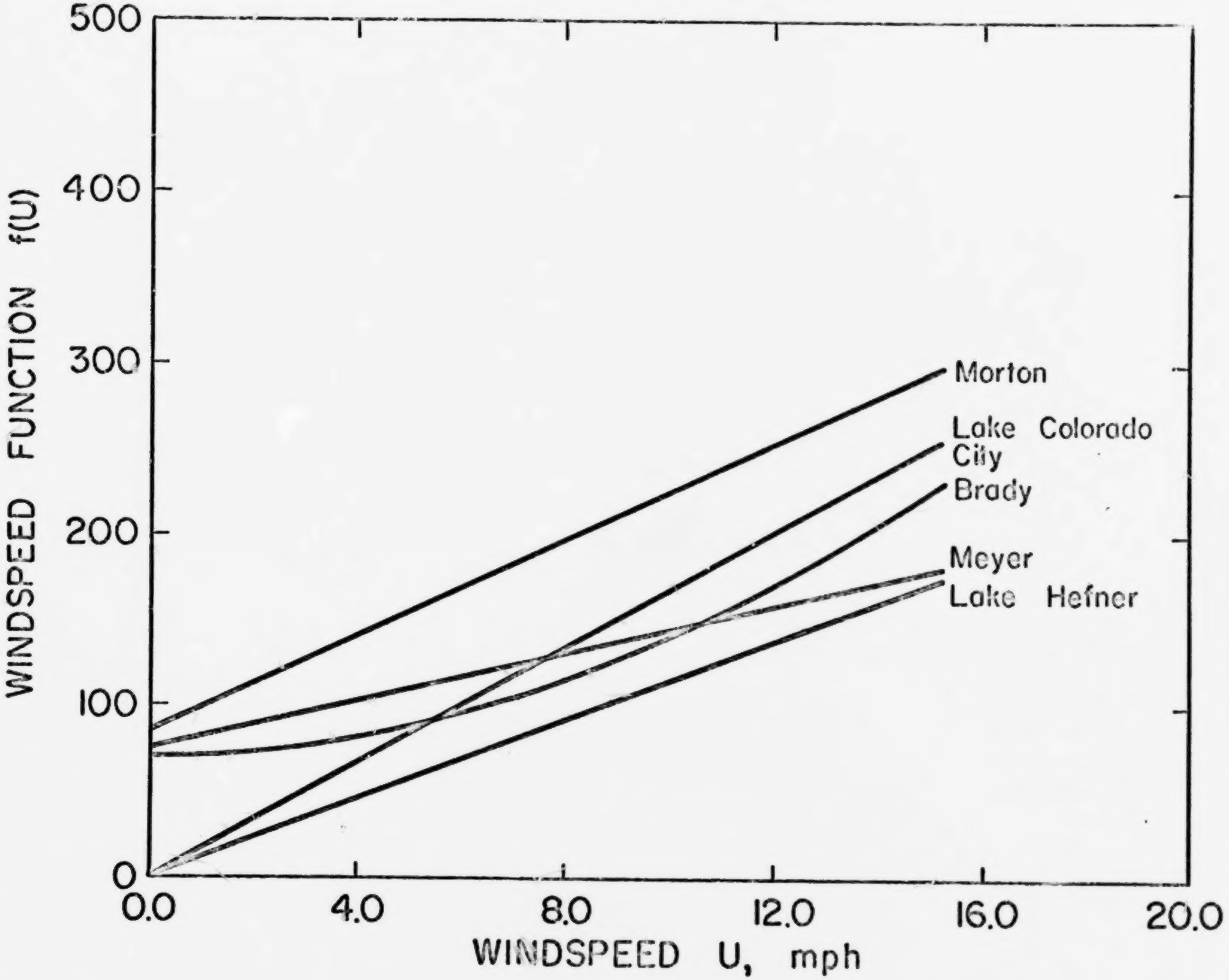


Fig. D-1 - Windspeed Function f(U) from Five Sources

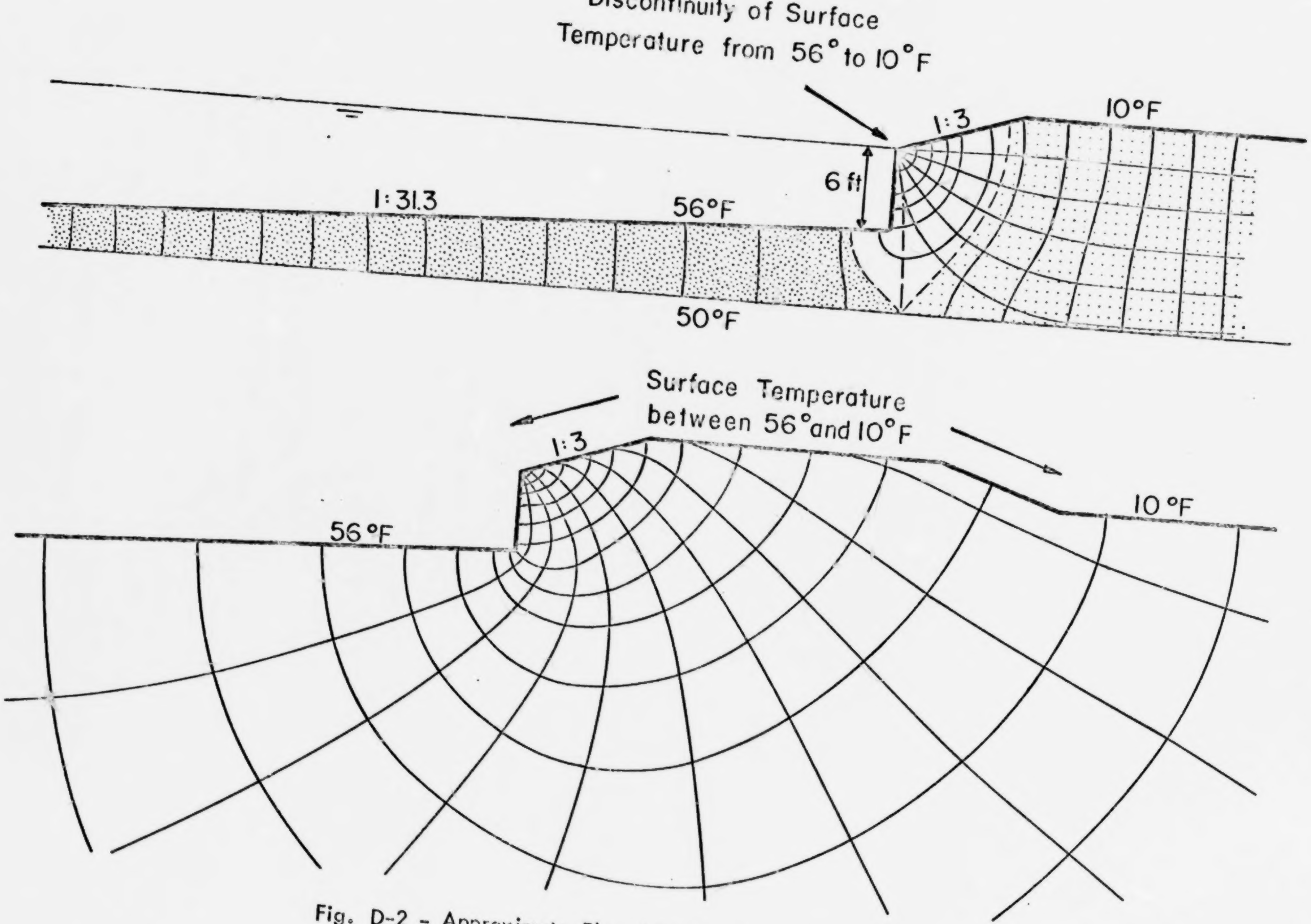

Discontinuity of Surface
Temperature from 56° to 10°F
1:3
10°F
6 ft
1:31.3
56°F
50°F
Surface Temperature
between 56° and 10°F
1:3
10 °F
56 °F

Fig. D-2 - Approximate Flow Nets for Heat Conduction through Soil

E. WATER BUDGET OF THE PONDS

1. Components

1.1 Precipitation

Precipitation in terms of mean monthly values has been given in Table C-6 and is reproduced on a daily basis in Table E-1.

1.2 Evaporation

Evaporation losses can be found by dividing the evaporative heat losses by the product of the latent heat of vaporization, $L = 144$ BTU-lb_m^{-1}, and the density of water $\rho = 62.4\ lb_m\ ft^{-3}$. Evaporative heat loss for the hottest ponds was given in Table D-3, and the resultant mean monthly evaporation values are shown in Table E-1. Comparison of the evaporation values in Table C-9 for a natural pond with those in Table E-1 for a heated pond shows that the heating increases the water losses by a factor of as much as 30.

1.3 Seepage

The river banks of the site are several feet high. For this reason, and also to provide protection from floods, the ponds will need to be constructed at such an elevation that their bottom is above the groundwater table. The ground consists of alluvial material of unknown permeability. The ponds will be sealed by a layer of clay approximately 6 in. thick covered by 2 in. of Gunite. Seepage losses through such a two-layered system can be estimated from the relationship

$$q_{seep} = \frac{h}{\left(\frac{s_1}{k_1} + \frac{s_2}{k_2}\right)} \qquad \text{(E-1)}$$

where s and k designate the thicknesses and coefficients of permeability, the subscripts indicate the specific layer, and h is the available head, which under the above assumptions would be approximately the mean depth of the ponds, or 6 ft. The coefficients of permeability are as yet unknown. Therefore two extreme values will be roughly estimated: a maximum of 1 gal day^{-1} ft^{-2} and a minimum of 0.001 gal day^{-1} ft^{-2} for both layers.

The resultant seepage values will be 14.4 in. day^{-1} and 0.014 in.-day^{-1}. A value of 0.5 in. day^{-1} appears to be reasonable if the ponds are well built, and this figure has been used in Table E-1.

In winter, average freezing depths in agricultural soils near the site amount to 40 to 50 inches, according to Ref. [12]. The maximum depths of frozen agricultural soils are close to 60 inches. The average depth of the heated pond is 72 inches. Consequently, seepage losses will probably not change very much with the season.

2. Total Water Budget

The pond volume is to be kept constant; there is no long-term change in storage. Therefore if the arithmetic sum of precipitation, evaporation, and seepage furnishes a total which is other than zero, make-up water has to be added to the pond. The required mean monthly values of make-up water are shown in the last column of Table E-1. Here 1.0 in. day^{-1} of water lost from a surface of 10,900 sq ft corresponds to a flow rate of 0.0105 cfs. A water supply system for a maximum discharge of 0.0105 x 4.3 = 0.047 cfs discharge must therefore be provided for every pond. The main water loss apparently occurs by evaporation.

If the make-up water is well water, it seems advisable to expose it in summer to the atmosphere by placing it in a temporary holding pond before adding it to the ponds which require heating. This procedure will usually change its temperature in the right direction before it is brought into contact with the pond water. It is safe to assume that the temperature difference can be kept to 20°F by the suggested temporary storage of well water on the surface. The amount of additional heat required to change the temperature of the make-up water to the pond water temperature can be obtained by multiplying the values in the last column of Table E-1 by the product $\rho c_p \Delta T$, where $\rho = 62.4\ \mathrm{lb_m\ ft^{-3}}$, $c_p = 1\ \mathrm{BTU\ lb_m^{-1}\ {}^{o}F^{-1}}$, and ΔT is the temperature deficit of the make-up water. A water deficit of 1.0 inch/day represents a heat requirement of 104 BTU ft^{-2} day^{-1} at a 20°F temperature deficit. Make-up water for cooled ponds can be added directly, since it will produce direct cooling in summer and heating in winter as necessary, anyway.

If make-up water is added at a constant flow rate for all ponds, the coldest ponds will have a substantial overflow because of their smaller evaporation rate. Also, rainfall will produce overflow in all ponds at some times. A drain must therefore be provided. Furthermore, because of the daily differences in evaporative water losses, make-up water additions or pond levels will fluctuate around their normal values. Differences in level up to ± 12 inches may occur in heated ponds if the make-up rate is fixed. It appears advisable to stop the flow of make-up water during periods of maximum heat requirements in midsummer (July - August) to conserve heat; this will cause the pond level to drop. The design discharge of the make-up water system should be at least twice the maximum mean monthly value; 0.1 cfs per pond appears to be reasonable. It is also noteworthy that the water losses from the ponds as shown in Table E-1 are so large that in July a volume equivalent to the total volume of water in the pond will be lost in $5.9 \times \frac{12}{4.5} = 15.7$ days. This is the average monthly rate.

A seepage loss of 0.5 in. of water per day or less has been anticipated. Seepage losses are compensated for by addition of make-up water (well water) to the pond. Make-up water in excess of the required 0.5 in. of water can be provided, but it may result in substantial changes in pond water quality. The ponds are likely to be built above the groundwater table. If leaks develop it will be very difficult to locate them. Therefore great care should be taken in the design and construction of the pond seal. In doing this it should be anticipated that small differential settlements in the pond bottom will occur. Therefore a somewhat flexible sealing layer should be used. It should be determined whether a layer of Gunite is adequate for that purpose or whether it is likely to crack under a load of 6 to 8 ft of water. Excavation of the ponds would seem desirable from this point of view, because the removal of soil and its replacement by water would result in smaller changes in the soil stress distributions than the addition of a load of water on the soil surface. Critical stress conditions are most likely to develop where rigid concrete elements join the Gunite blanket around the edge of the pond. The transition from the Gunite to the concrete should be designed carefully. Flexibility must be provided at these points. This can be achieved by using various kinds of seals of which clay is probably the simplest.

Table E-1

MEAN MONTHLY WATER BUDGET OF HOTTEST POND
IN INCHES OF WATER PER DAY

Month	Precipitation	Calculated Evaporation	Estimated Seepage	Total Water Increment
Jan	+0.02	-1.96	-0.5	-2.4
Feb	+0.03	-1.94	-0.5	-2.4
Mar	+0.04	-1.92	-0.5	-2.4
Apr	+0.06	-1.52	-0.5	-2.0
May	+0.11	-2.60	-0.5	-3.0
June	+0.15	-3.17	-0.5	-3.5
July	+0.11	-4.11	-0.5	-4.5
Aug	+0.12	-3.73	-0.5	-4.1
Sept	+0.08	-2.94	-0.5	-3.4
Oct	+0.05	-3.31	-0.5	-3.8
Nov	+0.04	-2.30	-0.5	-2.8
Dec	+0.02	-1.95	-0.5	-2.4

F. MAIN FEATURES OF POND HEATING AND COOLING SYSTEMS

1. Preliminary Considerations

The direct addition of hot or cold water to the ponds would be the simplest method of controlling temperature. However, this method was considered undesirable in view of water quality considerations. Therefore, design studies were confined to internal and external heating systems without mass transfer (except for make-up water). The main results of design calculations on several systems are presented in the following paragraphs.

On the basis of preliminary information the NWQL decided that an external heat exchanger system would provide the most desirable solution because it would interfere least with methods of sampling in the pond and would preserve the bottom of the pond in a more or less natural form. The external heat exchanger solution will therefore be examined in more detail than other solutions; its design features are found in section 3. The design features of several forms of internal heat exchangers are described first in section 2.

2. Internal Heat Exchangers

2.1 Parallel Pipes Below Bottom of Pond

The first alternative considered was heating the pond through pipes buried under the bottom of the pond. In this case the heat is transmitted by conduction through the pipe walls and through the bottom material of the pond. Natural convection carries it into the interior of the pond. An arrangement consisting of parallel pipes placed horizontally in the bottom of the pond was contemplated. The approximate heat flux per linear foot of pipe can be found from the analogy with the equivalent seepage problem into drain pipes. Reference [21] indicates on page 374 that the seepage rate for an infinite number of parallel, horizontal drainage pipes at a distance ℓ from each other is, in dimensionless form,

$$\frac{Q}{k(h - h_{dr})} = \frac{2\pi}{\ln \sinh^2(\frac{2\pi s}{\ell}) - \ln \sinh \frac{\pi r}{\ell}} = f(\frac{s}{\ell},\frac{r}{\ell}) \qquad \text{(F-1)}$$

where Q is the discharge per unit length of pipe, k is the coefficient of permeability, h is the head applied uniformly on the horizontal surface,

h_{dr} is the head at the contour of the drainage pipe, s is the distance from the surface of the ground to the center of the pipe, and r is the radius of the pipe, which is assumed to be small compared to s. The right-hand side of the equation is a coefficient which depends merely on the geometry of the flow field. Its value has been found numerically for small pipes placed at shallow depths below the bottom of the pond.

If the equation is applied to a heat flow problem, the following substitutions must be made: the heat flow rate per unit length of pipe q for Q, the thermal conductivity of the soil k_s for k, the pond water temperature T_s for h, and the temperature at the surface of the pipe T_e for h_{dr}. The result, in dimensionless form, is

$$\frac{q}{k_s(T_e - T_s)} = f(\frac{s}{\ell}, \frac{r}{\ell}) \tag{F-2}$$

With a spacing ℓ of the pipes the average rate of heat flux per surface area is

$$H = \frac{q}{\ell} = \frac{k_s(T_e - T_s)}{\ell} f(\frac{s}{\ell}, \frac{r}{\ell}) \tag{F-3}$$

Ref. [22], p. 594, indicates a thermal conductivity for a wet soil of $k \approx 1.5$ BTU hr^{-1} ft^{-1} $^oF^{-1}$. The available temperature difference $T_e - T_s$ is at most 12°F if the specified pond water temperatures are to be attained. The largest physically possible value of f is obtained if $s/\ell = 1/2$ and $r/\ell = 1/2$; in this case $f(s/\ell, r/\ell) = 1.55$. The mean heat flux associated with these figures is

$$H = \frac{1.5 \times 12.0}{0.25} \times 1.55 \times 24 = 2680 \text{ BTU day}^{-1} \text{ ft}^{-2}$$

This value is a little over one-half of the minimum required value. Therefore a system of pipes buried in the bottom cannot be used. The heat transfer capacity would be insufficient.

The previous calculations make the assumption that the temperature on the bottom of a pond would be uniform. In reality the heat may not actually be carried away from the bottom by convection in the pond water fast enough to produce uniformity of temperatures. In such a case the total heat fluxes would be less than the calculated values. More detailed and precise computations on this subject can be found in Appendix A-2.

2.2 Parallel Pipes above Bottom of Pond

If the heating pipes are placed within the pond, for example a few inches above the bottom, the pipes will act as heated cylinders and natural convection currents will be produced in the pond. The pipes may be horizontal and parallel. If they are far enough apart to avoid interference, the rate of heat transfer per unit length will be

$$q = \bar{h}_c(T_o - T_s)D_o\pi \tag{F-4}$$

where $\bar{h}_c$ is the average heat transfer coefficient for single, horizontal, heated cylinders; T_o is the temperature at the surface of the cylinder; T_s is the pond water temperature; and D_o is the outer diameter of the pipe.

The value of $\bar{h}_c$ can be found from standard references [22] if it is expressed in terms of the dimensionless Nusselt number, $Nu = \bar{h}_c D_o k^{-1}$. The rate of heat transfer is, then,

$$q = \pi k(T_o - T_s)Nu \tag{F-5}$$

It is known that the value of Nu in a specific problem in free convection depends on the product of two other dimensionless numbers:

the Grashoff number $$Gr = \frac{\rho^2 g\beta}{\mu^2} D_o^3(T_o - T_s) \tag{F-6}$$

and the Prandtl number $$Pr = \frac{c_p\mu}{k} \tag{F-7}$$

where ρ is the density of the fluid in $lb_m\ ft^{-3}$, g is the acceleration of gravity in ft sec^{-2}, β is the coefficient of thermal expansion in 1/R, μ is the dynamic viscosity in $lb_m\ sec^{-1}\ ft^{-1}$, c_p is the specific heat in BTU $lb_m^{-1}\ {}^oF^{-1}$, and k is the thermal conductivity in BTU hr^{-1} $ft^{-1}\ {}^oF^{-1}$. For practical purposes empirical equations or graphs of the form

$$Nu = \phi(Gr, Pr)$$

such as those given by McAdams and reproduced in Ref. [22], page 334, can be used. Numerical computations were carried out for three pipe diameters D_o and four temperature differentials $(T_o - T_s)$ as shown in Table F-1.

The NWQL considered that temperature differentials of more than 5°F between the pipe surface and the pond water might be detrimental for the purposes of their experiments. If the minimum spacing between pipe centers, ℓ, is two times the diameter of a pipe (which will probably violate the assumption of no interference), the average heat input per unit area $H = q/\ell$ is

$$\begin{aligned} \text{for } D_o &= 1 \text{ in.,} & H &= 58.8 \times 6 \times 24 = 8470 \text{ BTU ft}^{-2} \text{ day}^{-1} \\ D_o &= 3 \text{ in.,} & H &= 122 \times 2 \times 24 = 5850 \text{ BTU ft}^{-2} \text{ day}^{-1} \\ D_o &= 6 \text{ in.,} & H &= 204 \times 1 \times 24 = 4900 \text{ BTU ft}^{-2} \text{ day}^{-1} \end{aligned}$$

If the spacing is three times the diameter of the pipe, the average heat input per unit area H is

$$\begin{aligned} \text{for } D_o &= 1 \text{ in.,} & H &= 58.8 \times 4 \times 24 = 5640 \text{ BTU ft}^{-2} \text{ day}^{-1} \\ D_o &= 3 \text{ in.,} & H &= 122 \times 4/3 \times 24 = 3900 \text{ BTU ft}^{-2} \text{ day}^{-1} \\ D_o &= 6 \text{ in.,} & H &= 204 \times 2/3 \times 24 = 3260 \text{ BTU ft}^{-2} \text{ day}^{-1} \end{aligned}$$

The heat fluxes shown above must also be transmitted through the walls of the heating pipes. The temperature differentials required to do this can be calculated from the conduction equation. The pipes will have thin walls such that the heat fluxes per foot length will be approximately

$$q = \frac{k_w(T_i - T_o)\pi D_o}{e} \tag{F-8}$$

where k_w is the thermal conductivity of the pipe material, e is the wall thickness, and $T_i - T_o$ is the temperature differential between the inside and the outside of the wall. For polyethylene pipes with a 1/16-in. wall thickness and thermal conductivities of 8×10^{-4} cal sec^{-1} cm^{-2} ^{o}C^{-1} cm (approx. 0.19 BTU hr^{-1} ^{o}F^{-1} ft^{-1}), the required temperature differentials $T_i - T_o$ for heat fluxes given in lines 2 and 6 of Table F-1 are

$$D_o = 1 \text{ in.,} \quad T_i - T_o = \frac{q_e}{k_p \pi D_o} = \frac{58.8}{0.19 \times 16 \times 3.14} = 6.1^{o}\text{F}$$

$$D_o = 3 \text{ in.,} \quad T_i - T_o = \frac{122}{0.19 \times 16 \times 3 \times 3.14} = 4.2^{o}\text{F}$$

The total temperature difference between the interior of the heating pipe and the surrounding pond water would be

$$T_i - T_s = (T_i - T_o) + (T_o - T_s) \quad \text{(F-9)}$$

For

$$D_o = 1 \text{ in.,} \quad T_i - T_s = 6.1 + 5.0 = 11.1^\circ F$$
$$D_o = 3 \text{ in.,} \quad T_i - T_s = 4.2 + 5.0 = 9.2^\circ F$$

The margin between these values and the assumed 12°F total difference could be used to account for losses in the pipeline system between the power plant and the exit from the internal heat exchanger. More detailed computations on free convection heat transfer are given in Appendix A-3.

In summary, the ponds can be heated using natural convection if plastic pipes of one-to-two-inch diameter are installed at spacings of approximately three times their diameter on the bottom of the pond. If larger diameters are used, the spacing can be only two times the pipe diameters. The pipes can be connected to two headers which would distribute the heating water uniformly into all pipes.

The effects of the bottom on the free convection and the rates of heat transfer can only be guessed at. It is conceivable that a warm water layer might form in the space between the pipes and the bottom. This would indicate that only the upper half of the pipe heats the pond water, because the warm water around the lower half would not be removed. It is also difficult to predict how the rates of heat transfer would change if the pipes were placed directly on the bottom or if the spaces between the pipes were filled by deposits. Experiments should be carried out to clarify these questions if a system like this is contemplated.

The internal heat exchanger system is feasible. It was rejected by the NWQL for three reasons: First, a system of pipes above the bottom of the pond would render the sampling of fish difficult (fish would tend to hide between or underneath the pipes). Second, it is also conceivable that a hot-water film would form underneath the pipes and that temperatures in the mud beneath them might be excessive and affect animal life. Third, a large bottom area would be occupied by the pipes.

The internal heat exchanger system can be used for cooling only in combination with a device which mixes the pond water constantly, and this is a disadvantage. It is necessary to remove the cold water from the bottom of the pond to prevent stratification.

3. External Heat Exchangers

3.1 General Layout

In an external heat exchange system, water is pumped from a pond through a heat exchanger and discharged back into the pond. Pond water is never mixed with heating or cooling water with the exception of make-up water. Figure F-1 shows schematically possible layouts for a series of ponds with different temperatures (two ponds always being identical, however).

The flow direction in the recirculating pipe system sketched in Fig. F-1a changes when the pond control switches from heating to cooling, and vice versa, based on the assumption that occasional reversal of the flow direction would help to keep the screens in front of the inlet and the outlet clean. Flow reversal would also help to prevent stratification in the pond if inlet and outlet were located at different elevations. However, there are other means of preventing the clogging of screens and stratification. In view of the required screen sizes discussed in section 3.3 it may not be desirable to reverse the flow direction. Such a modification would also simplify operation of the system somewhat. An irreversible system is shown in Fig. F-1b.

A temperature change of $\pm 6^oF$ in the heat exchanger is planned. This is based on the assumption that 1^oF is lost or gained in the underground pipe system through which the pond water is recirculated as shown in Fig. F-2. (Calculations on the heat loss from underground pipes are presented in a subsequent section.) The remaining useful temperature difference will then be 5^oF above or below the existing pond temperature for heating or cooling, respectively, and this is acceptable to the NWQL. This value combined with a design heat flux of $H_n = 4800$ BTU ft^{-2} day^{-1} for the hottest pond results in the following volumetric design flow rate Q through the heat exchanger:

$$Q = \frac{H_n A_s}{\Delta T_H c_p \rho} = \frac{4800 \times 10{,}900}{5.0 \times 1.0 \times 62.3 \times 24 \times 3600} = 1.94 \text{ cfs}$$

The design of the water recirculation system should therefore be based on a recirculation rate of at least $Q = 2.0$ cfs for each pond. For a design heat flux of 6300 BTU ft^{-2} day^{-1} and the same temperature differences, Q would have to be 2.55 cfs.

It is understood that in actual operation the rate of recirculation would be the same for all ponds at any given time. The amounts of heat added to or withdrawn from the pond water would be varied by changing the amount of heating or cooling water flowing through the heat exchanger. In other words, water temperatures are adjusted by changing the flow rates in the external circuit of the heat exchanger. The internal flow rates are identical for all ponds. (They may change periodically for all ponds together, but this will not affect the design values.)

At a recirculation rate of 2.0 cfs the total water volume in a pond, which is approximately 64,000 cu ft, will be circulated through the heat exchanger 2.7 times every day. This appears to be a large value, and daily adjustments of the internal circulation rate may be preferable to constant flow operation.

The available amount of heating water is 2800 gpm (6.2 cfs) assumed to be at 12°F above the hottest pond temperature. If the ponds are operated in series and in pairs with identical temperatures as suggested in Fig. F-1, the approximate temperature drop produced across the heat exchanger for the hottest pond is that shown at the top of Fig. F-2.

The available amount of cooling water is 40 to 80 gpm, or 0.09 to 0.18 cfs, assumed to be at 50°F. This is roughly a little more than the maximum amount of make-up water required. It is entirely insufficient for producing the water temperatures listed in Appendix B-2. If well water of 50°F were added directly to two ponds at a water temperature of 67°F, when the design cooling rate had to be 4800 BTU ft^{-2} day^{-1}, a flow of

$$2Q = 2 \times \frac{4800 \times 10{,}900}{(67 - 50) \times 62.3 \times 1.0 \times 24 \times 3600} = 1.14 \text{ cfs}$$

would be required. If the well water is sent through a heat exchanger which changes its temperature by only 10°F, the required flow rate for the same two ponds is close to 2.0 cfs. In other words, an external heat exchanger will require well water at a rate of 2.0 cfs or 900 gpm if pond water temperatures near 65°F are to be achieved in midsummer. The temperature changes across the heat exchanger in the cooling cycle for the coldest pond with the 2.0 cfs rate of well water flow are shown at the bottom of Fig. F-2.

3.2 Pipe Systems

The main pipe characteristics for an external heat exchanger system like that sketched in Fig. F-1 can be chosen as follows:

Main Heating Water Line:

Diameter: 12 in.
Length: Less than 2500 ft
Wall Thickness: 13/64 in.
Material: Steel, welded joints, coated and wrapped, insulated with 1-in. foamglas

Design Flow Rate: 2800 gpm or 6.2 cfs

Average Flow Velocity: 7.9 fps

Estimated Headloss for 2500
ft of Straight Horizontal pipe: 40 ft

Estimated Additional Headloss for
One regular elbow: 0.30 ft
One gate valve, wide open: 0.19 ft

Main Cooling Water Line:

Diameter: 8 in.

Length: Less than 2500 ft

Wall Thickness: 13/64 in.

Material: Same as above

Design Flow Rate: 2.0 cfs or 900 gpm

Average Flow Velocity: 5.7 fps

Estimated Headloss for 2500
ft of Straight Horizontal Pipe: 29 ft

Estimated Additional Headloss for
One regular elbow: 0.16 ft
One gate valve, wide open: 0.10 ft

By-Pass Lines:

Same as main lines

Recirculating Pipes:

Diameter: 8 in.

Length: Less than 500 ft per line

Wall Thickness: 13/64 in.

Material: Choice of steel insulated with 3-in. foamglas, PVC, polyethylene or asbestos-cement

Design Flow Rate: 2.0 cfs per pond

Average Flow Velocity: 5.7 fps

Estimated Headloss in 500 ft
of Horizontal Steel Pipe: 4.4 ft

Estimated Additional Headloss in
One regular elbow: 0.30 ft
One gate valve, wide open: 0.19 ft

Estimated Additional Headlosses in PVC, polyethylene or asbestos-cement pipes are of similar magnitude.

Make-Up Water Line:

Diameter: 2 in.
Length: Less than 500 ft per line
Wall Thickness:
Material: Choice of steel, PVC or polyethylene
Design Flow Rate: 0.1 cfs
Average Flow Velocity: 4.6 fps
Estimated Headloss in 500 ft
of Horizontal Steel Pipe: 25 ft

All pipes should be underground for frost protection. Heat exchangers may have to be installed in pits for the same reason. Heat losses through the pipe walls must be kept small, and therefore insulation with one inch of foamglas appears desirable for the main pipes. Foamglas 3/4 in. thick will be sufficient for the recirculation pipes if they are built of steel, although PVC, polyethylene or asbestos-cement pipes may be chosen instead. Insulation is not desirable for the make-up water lines.

The heat loss through the walls of the main lines is essentially controlled by the insulation as specified. The temperature drop over a 2500 ft length of pipe can be roughly calculated from the approximate relationship

$$\Delta T_{pipe} = \frac{(T_i - T_o)\, k_{insul}\, D\pi L}{e\, Q\, c_p\, \rho}$$

where T_i is the mean water temperature in the pipe, T_o is the temperature at the outer edge of the insulation, k_{insul} is the thermal conductivity of the insulation material, D is the diameter of the pipe, L is the length of the pipe, e is the thickness of the insulation material, Q is the flow rate through the pipe, c_p is the specific heat, and ρ is the density of water. Appropriate design values for the heating water main are $T_i = 68^\circ F$; $T_o = -20^\circ F$; $k_{insul} = 0.09$ BTU $hr^{-1}\ ft^{-1}\ {}^\circ F^{-1}$; $D = 12$ in.; $L = 2500$ ft; $e = 1$ in.; $Q = 6.2$ cfs; $c_p = 1$ BTU $lb_m^{-1}\ {}^\circ F^{-1}$; and $\rho = 62.3\ lb_m\ ft^{-3}$. With these values a temperature drop of

$$\Delta T_{pipe} = 0.53^\circ F$$

is obtained. Up to 2°F is acceptable, and thus the contemplated design for the main pipes appears to be satisfactory. It may also be noted that since Q is in the denominator of the above equation, unacceptably large temperature drops occur if the flow rate in the main pipes is reduced very much.

A more accurate evaluation of the temperature drop in the water along the pipe was also made. Conduction through the insulating material and through the soil was taken into consideration. It was found that the temperature drop along the 2500 ft long pipe was 0.26°F for a 12 in. diameter pipe and 0.33°F for an 18 in. diameter pipe. If the pipe were placed on the surface of the ground and thus exposed to wind, the temperature drop would be 0.56°F for a 12 in. diameter pipe and 0.82°F for an 18 in. diameter pipe in a 50 mph wind. It can thus be concluded that one inch of foamglas insulation on the main water supply pipes is sufficient to prevent any major changes of water temperatures in these pipes. Similarly, 3/4 inch of foamglas insulation was found to be sufficient for the smaller and shorter recirculation pipes.

Similar calculations for PVC or polyethylene pipes show that these also require some kind of temperature insulation if temperature differentials between heat exchanger and pond are not to exceed 0.5°F as shown in Fig. F-2.

Although estimated head losses in the piping system have been calculated and are given in the preceding tabulation, the required pumping heads for the main pumps and the recirculation pumps can be evaluated only after additional information is available on the final elevations of the pond water surface, on the groundwater level, and on the head losses in the heat exchangers.

Some thought was given to the probable size of the heat exchangers. If the heat exchangers are single pass counterflow heat exchangers built of ordinary steel, the overall unit conductance U is likely to be of the order of 250 BTU ft^{-2} hr^{-1} $^oF^{-1}$. With this value it is found that the required heat transfer area is of the order of 500 sq ft. This is a large, but reasonable value. The final design of the heat exchanger should be obtained from a manufacturer. The data in Fig. F-2 specify the requirements. Figure F-1a also shows a heat exchanger in the make-up water and recirculation lines. This equipment would be used only in summer to increase the make-up water temperature before it was added to the pond. It is optional, but desirable for the hottest ponds.

3.3 Circulating Water Intakes and Outlets to the Ponds

Ponds absorb or lose heat mainly through the water surface, as was shown in part D. Therefore a water layer at the pond surface will usually have a temperature different from the nominal pond water temperature. When this layer is colder than the pond water, it will sink to the bottom by natural convection, and when it is warmer it will tend to remain on top. In the absence of wind this may lead to a stably stratified temperature regime in a pond with the warmer layer gradually growing in thickness by conduction.

To determine the temperature gradient produced by the sinking of colder water it is necessary to consider the convective motion for various rates of surface heat loss. A temperature differential of 3° to 4°F in the surface layer may develop as shown in Appendix A-3. Such a temperature differential at the surface will be quite common for the hotter (heated) ponds in summer and for practically all ponds in winter.

Figure F-3 shows schematically possible alternative locations of the inlet and the outlet. The schemes contemplate flow in one direction for heating and in the other direction for cooling. Notes on the sketches call attention to some of the disadvantages and advantages of each scheme.

In any event, since heat flows mainly through the water surface, changes in temperature are felt there first. Hence it appears desirable to design inlets and outlets in such a way that the water is always removed from the surface of the ponds as rapidly as possible so as to avoid large temperature fluctuations in the interior. This can be done most effectively by placing the outlets near the surface. It also seems advisable to distribute the discharge over a large area to avoid large shearing velocities while getting good distribution of the water. There seems to be an advantage in placing all screens in a vertical plane so that major debris drop off. Also, outlets should be placed a short distance below the water surface so that they will be little affected by floating plants or objects.

In view of these considerations, the scheme shown in Fig. F-3, f.1, which has the flow direction the same in both heating and cooling cycles, seems appropriate for further discussion. The water is withdrawn in the shallow portions of the pond, and thus no temperature anomalies should be expected to develop in those areas. The inlet should be designed to produce a vertical mean flow. In the cooling cycle a temperature gradient in the vertical direction will develop, but it is expected to remain small because of the limitations imposed on water temperatures at the inlet and because withdrawal of water is strictly from the surface of the pond, where temperature changes are greatest.

Actually, the real relative merits of the various schemes depicted in Fig. F-3 cannot be evaluated without some experimental work on a physical model. A model study to select the best scheme would be desirable because of the three-dimensional circulation effects that are likely to occur in the ponds. Such patterns will have an important effect on the mixing in the pond, which will in turn affect the temperature distribution. Hopefully, model studies could eliminate the need for artificial mixing devices which might otherwise be required to remove water from stagnant areas.

The area of the inlet (or outlet) is determined by the inlet and outlet velocities and the type of screen. The NWQL has specified that the intake velocities should not exceed 0.1 fps to protect living organisms in the pond. At the discharge end, velocities may be as high as 0.2 to 0.3 fps. These velocities have been interpreted as the average flow velocities through the screen. The screen desired by the NWQL is a 40-mesh-per-inch stainless steel screen with a wire diameter of 0.01 in. and openings of 0.38 x 0.38 mm. Only 36 per cent of the total area of the screen is actually open to the flow. The required screen opening for a flow of 2 cfs per pond is about 20 sq ft. About 55 sq ft of screen are required to obtain this open area. Since screens of this kind have a tendency to be covered by trash quite rapidly, it is recommended that the actual screen size be over two times the required value, or 120 sq ft. A number of peripheral screen elements one foot high by 10 ft wide could be installed at the shallowest part of the pond for water withdrawal. One central screen at the deepest location in the pond could be 10 ft long by 6 ft wide and could serve as an inlet. Figure F-4 shows a possible arrangement of the peripheral screens. Self-cleaning, rolling type screens could be used instead of fixed ones.

The pressure differential across the screens can be found from the flow velocities in the contracted flow region at the screen: $v_i = 0.1$ fps inlet; $\Delta h = v_i^2/2g = 0.01/64.4 \approx 0.002$ in., and this is all but negligible.

The above computation assumes that only 55 sq ft of screen are open to the flow, the rest being plugged. If the screen is plugged completely, a much larger difference in head may develop. In the worst case the differential would be equal to the average depth of submergence of the top of the screen below the water surface. A screen placed close to the surface of the pond is an advantage from this standpoint.

Table F-1

FREE CONVECTION HEAT FLOW FROM SINGLE HORIZONTAL PIPE

D (in.)	$T_o - T_s$ (^oF)	Gr Pr	$\log_{10}$ Nu	Nu	Heat Flux q ($BTU\ hr^{-1}ft^{-1}$)
1	2.5	1.21×10^5	0.95	8.913	23.3
	5	2.42×10^5	1.05	11.22	58.8
	10	4.84×10^5	1.12	13.18	136
	20	9.68×10^5	1.2	15.85	331
3	2.5	3.28×10^6	1.31	20.42	53.4
	5	6.56×10^6	1.38	23.99	122
	10	13.12×10^6	1.43	26.92	282
	20	26.24×10^6	1.51	32.36	675
6	2.5	2.62×10^7	1.51	32.36	84.5
	5	5.24×10^7	1.6	39.81	204
	10	10.48×10^7	1.71	51.29	535
	20	20.96×10^7	1.8	63.10	1315

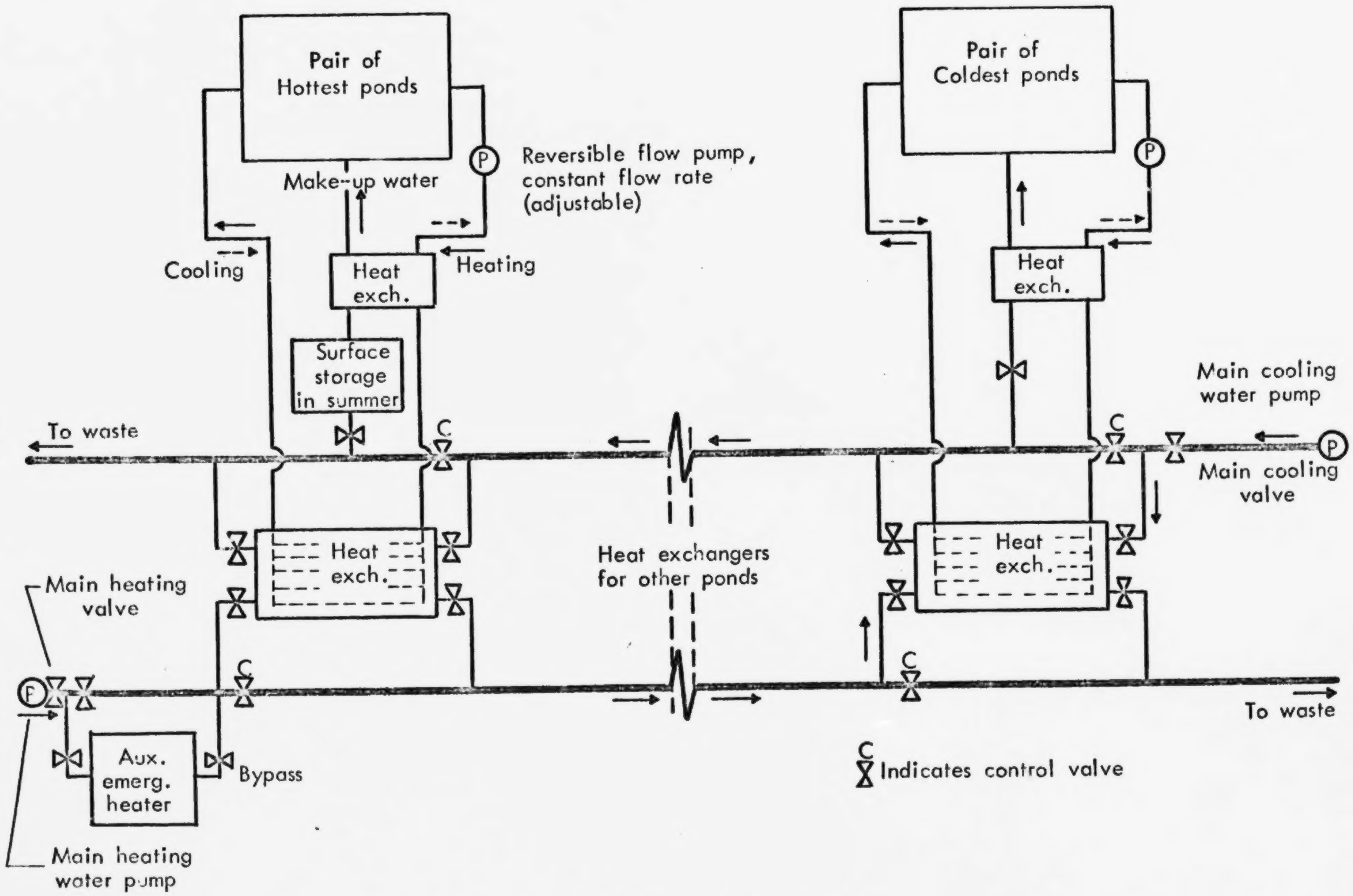

Pair of Hottest ponds
Make-up water
Reversible flow pump, constant flow rate (adjustable)
Cooling
Heating
Heat exch.
Surface storage in summer
To waste
C
Heat exch.
Main heating valve
Aux. emerg. heater
Bypass
Main heating water pump
Heat exchangers for other ponds
Pair of Coldest ponds
P
Heat exch.
Main cooling water pump
Main cooling valve
C
Heat exch.
C
To waste
C
Indicates control valve

Fig. F-1a - Reversible Pond Circulation System

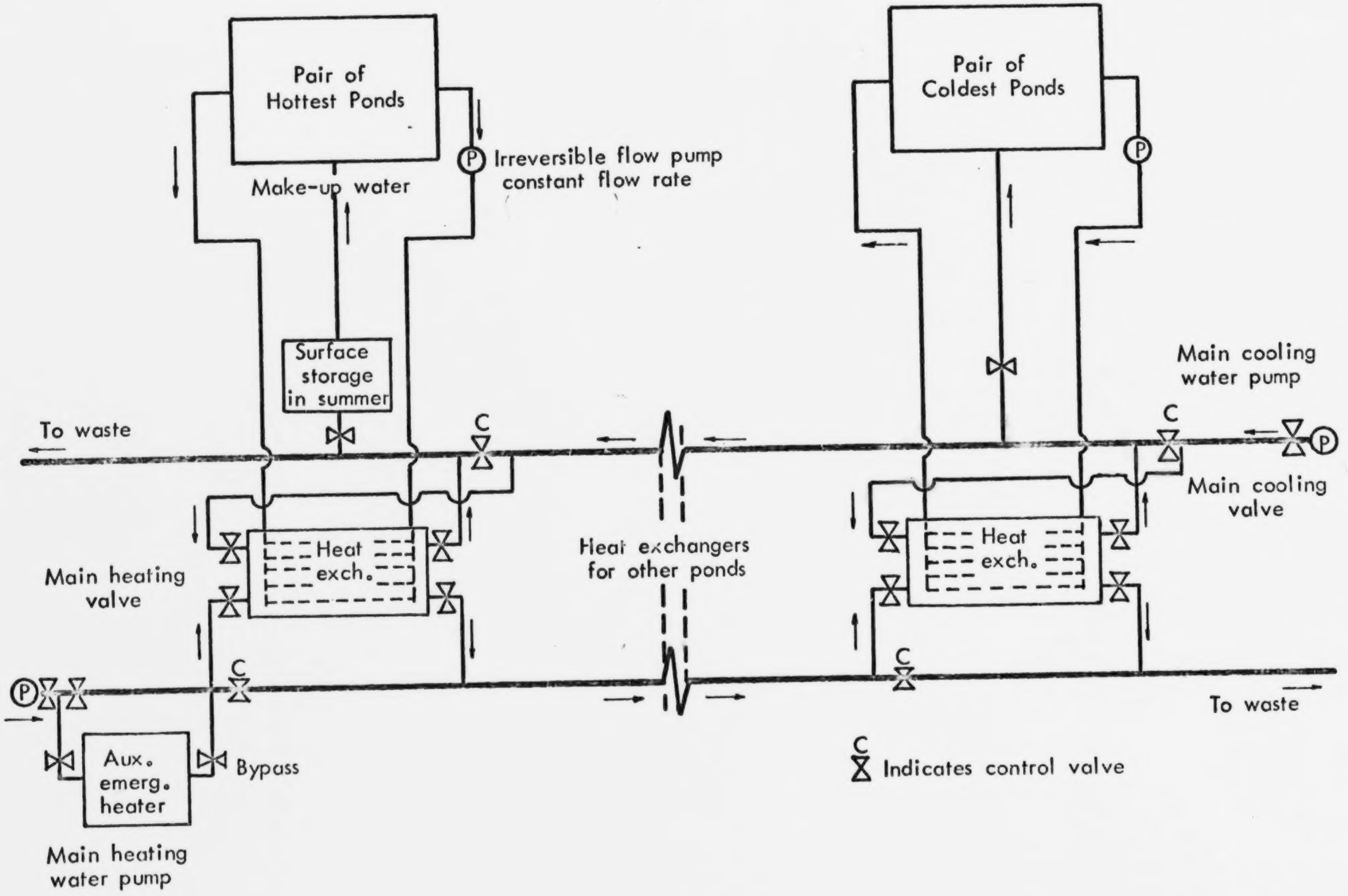

Pair of Hottest Ponds
Make-up water
Irreversible flow pump constant flow rate
Surface storage in summer
To waste
C
Heat exch.
Main heating valve
Aux. emerg. heater
Bypass
Main heating water pump
Heat exchangers for other ponds
Pair of Coldest Ponds
Main cooling water pump
Main cooling valve
To waste
C
Indicates control valve

Fig. F-1b - Uni-directional Pond Circulation System

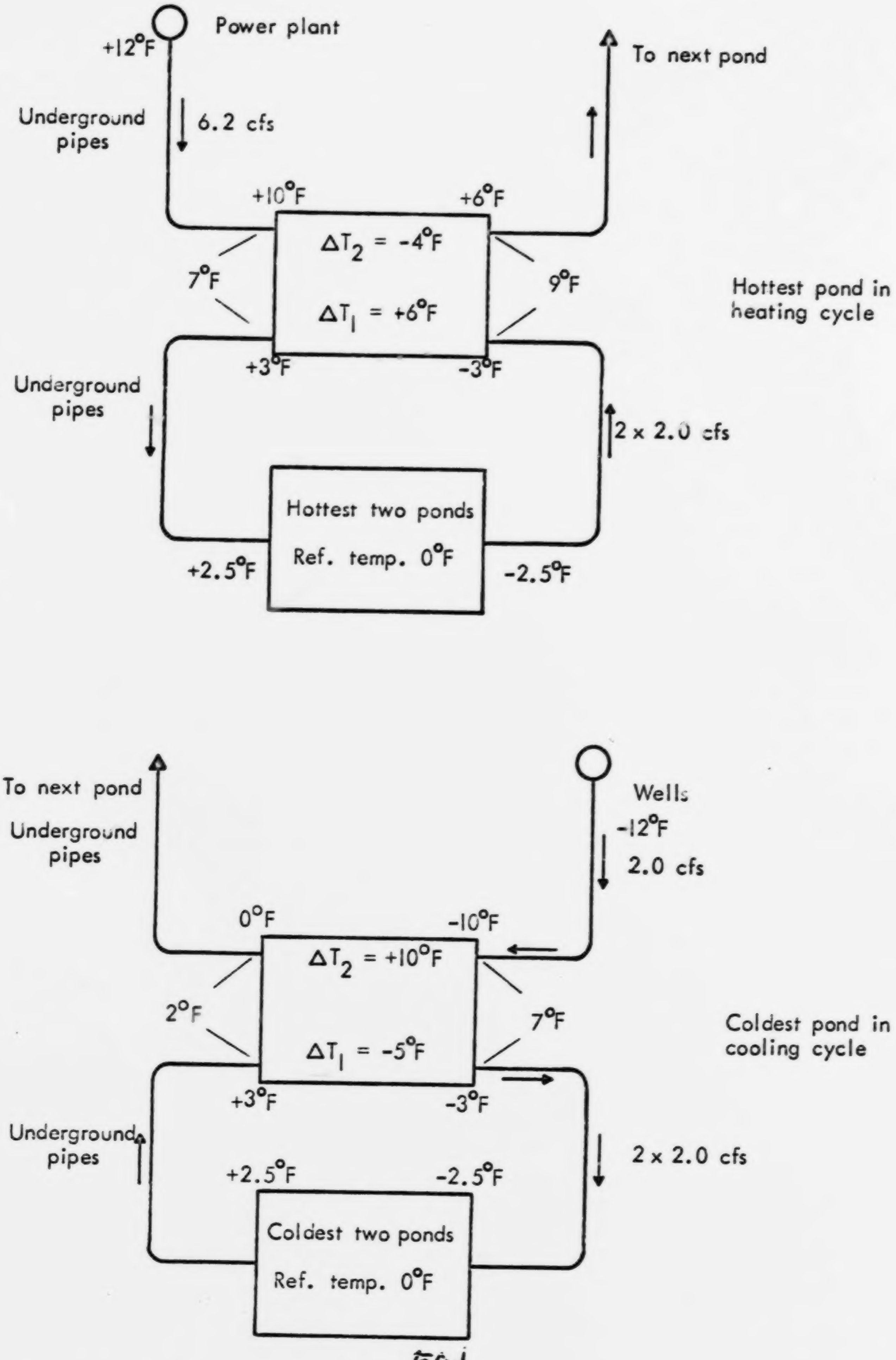
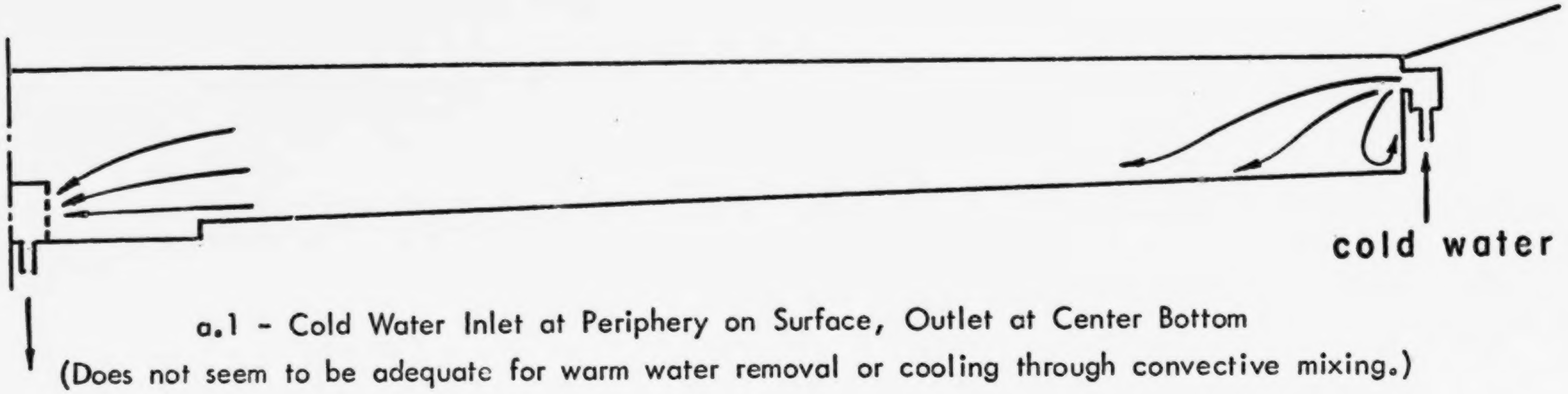
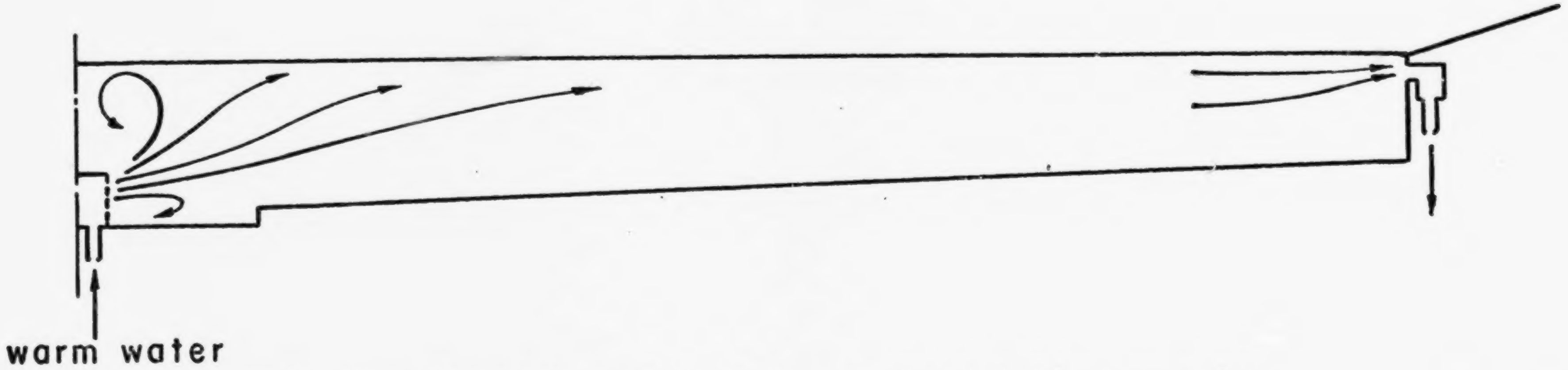

+12°F
Power plant
To next pond
Underground pipes
6.2 cfs
+10°F
+6°F
ΔT₂ = -4°F
7°F
9°F
ΔT₁ = +6°F
Hottest pond in heating cycle
+3°F
-3°F
Underground pipes
2 x 2.0 cfs
Hottest two ponds
Ref. temp. 0°F
+2.5°F
-2.5°F
To next pond
Wells
Underground pipes
-12°F
2.0 cfs
0°F
-10°F
ΔT₂ = +10°F
2°F
7°F
ΔT₁ = -5°F
Coldest pond in cooling cycle
+3°F
-3°F
Underground pipes
2 x 2.0 cfs
+2.5°F
-2.5°F
Coldest two ponds
Ref. temp. 0°F

Fig. F-2 - Sketch showing Temperature Differentials in Heat Exchanger System

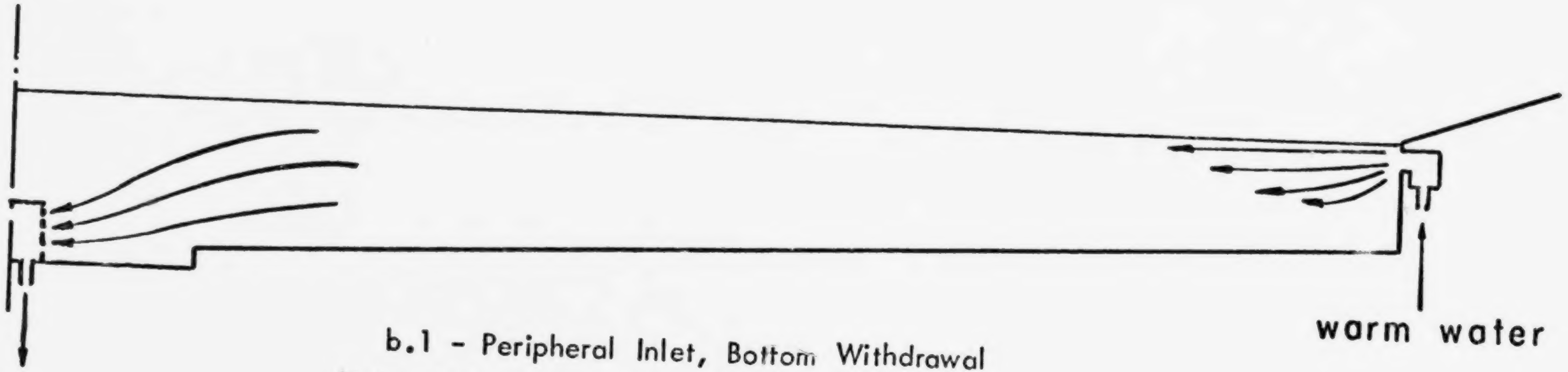


a.1 - Cold Water Inlet at Periphery on Surface, Outlet at Center Bottom
(Does not seem to be adequate for warm water removal or cooling through convective mixing.)

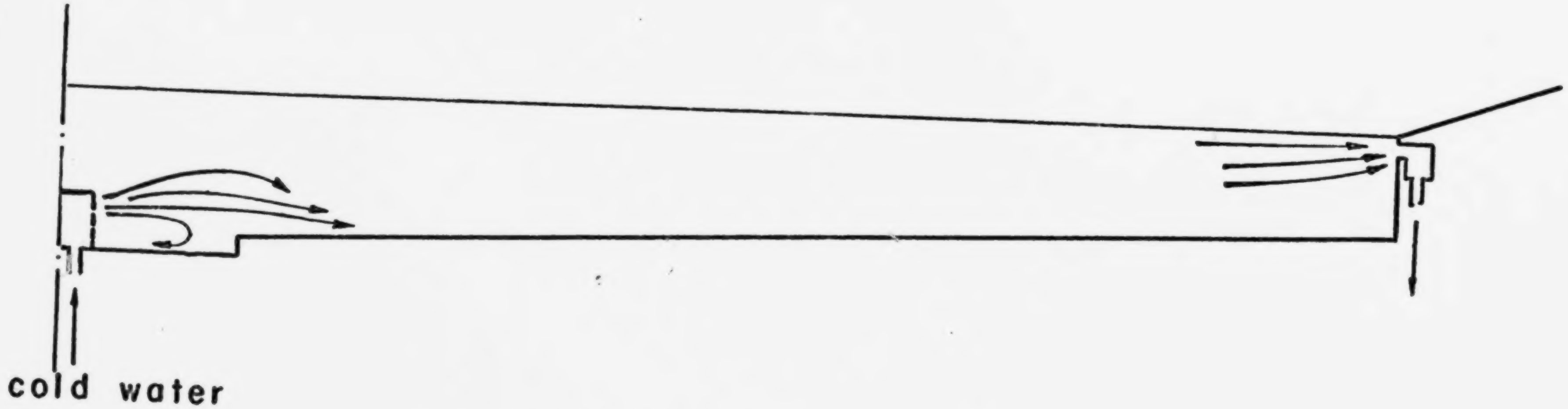


a.2 - Warm Water Inlet at Center Bottom, Outlet at Periphery on Surface
(Cool water neither mixed nor removed. There is a possibility of conserving heat through a thermal blanket effect.)

Fig. F-3 - Alternative Locations of Water Inlet and Outlet in a Pond

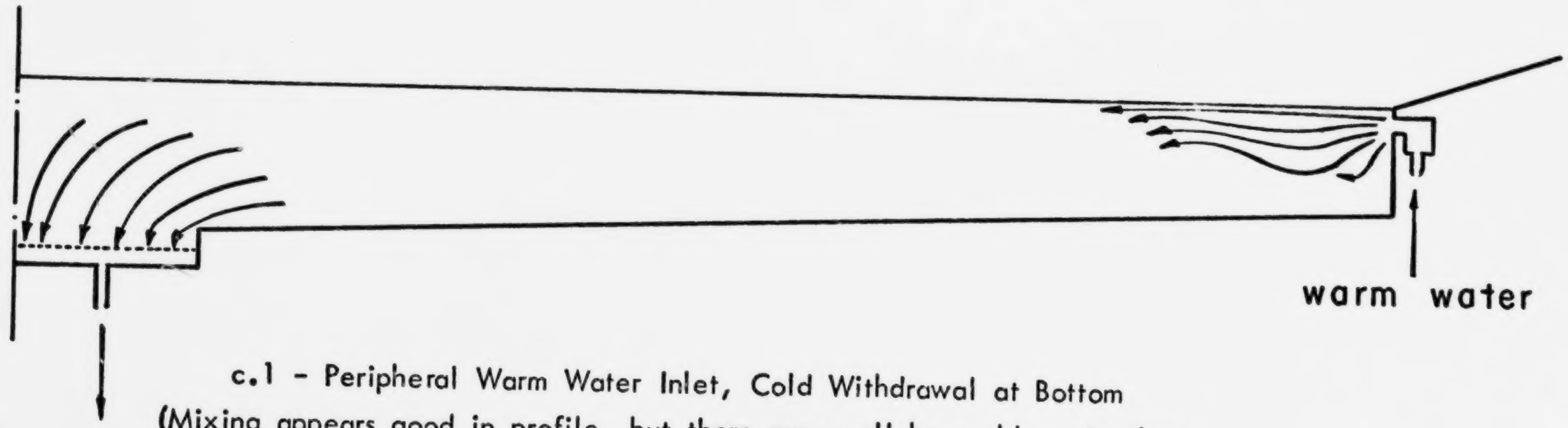


b.1 - Peripheral Inlet, Bottom Withdrawal
(Fair mixing and possible thermal blanketing effect.)

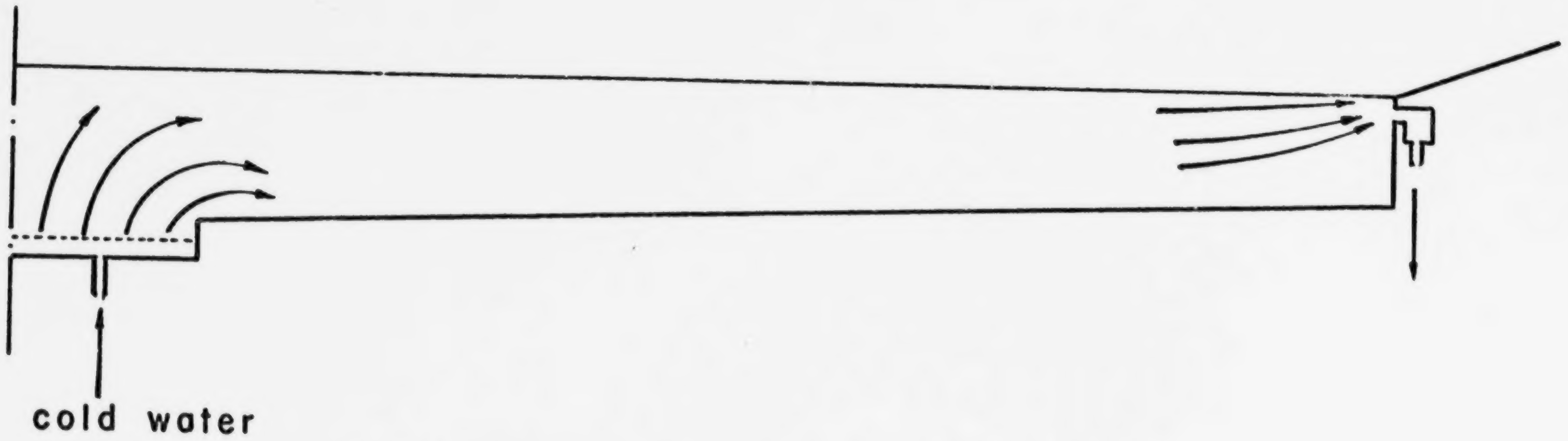


b.2 - Bottom Inlet and Peripheral Withdrawal
(Poor mixing - contributes to stratified condition; possible warm water pockets.)

Fig. F-3 - Alternative Locations of Water Inlet and Outlet in a Pond

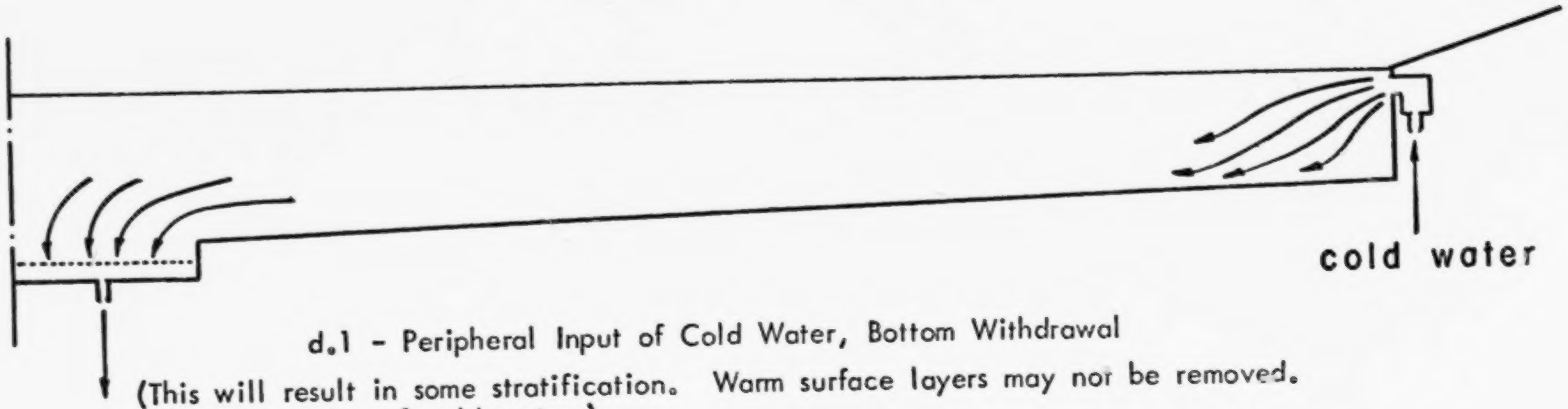


c.1 - Peripheral Warm Water Inlet, Cold Withdrawal at Bottom
(Mixing appears good in profile, but there may well be problems in that outlet is only 6 ft wide)



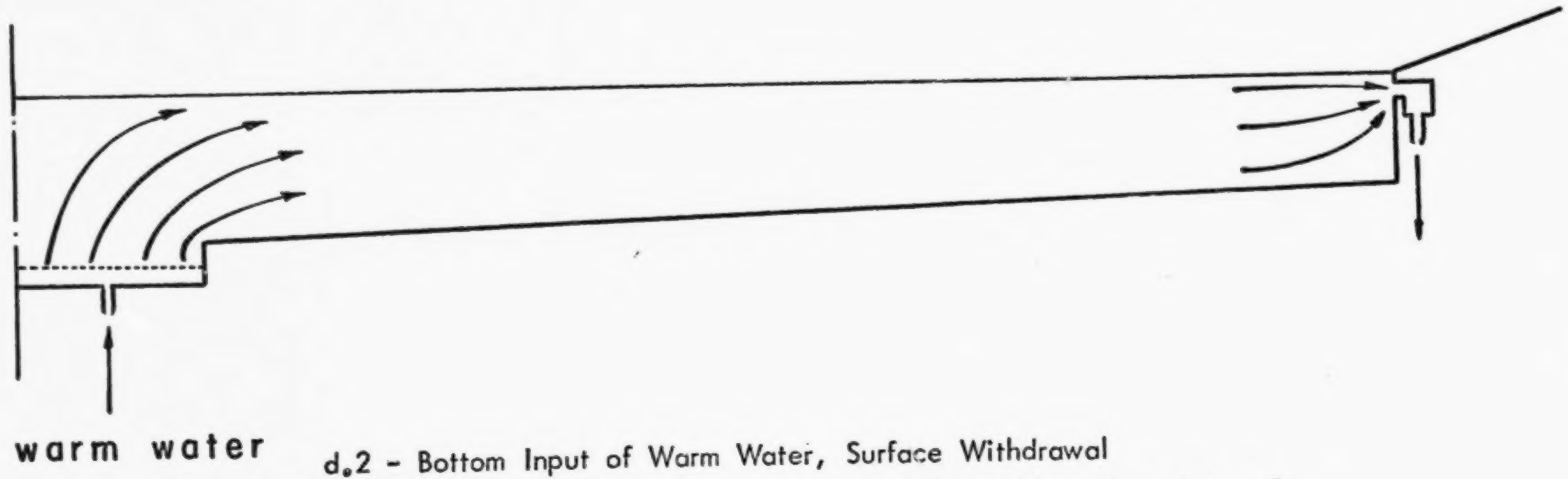
c.2 - Cold Water Input at Bottom, Peripheral Withdrawal
(Weak stratification possible)

Fig. F-3 - Alternative Locations of Water Inlet and Outlet in a Pond



d.1 - Peripheral Input of Cold Water, Bottom Withdrawal

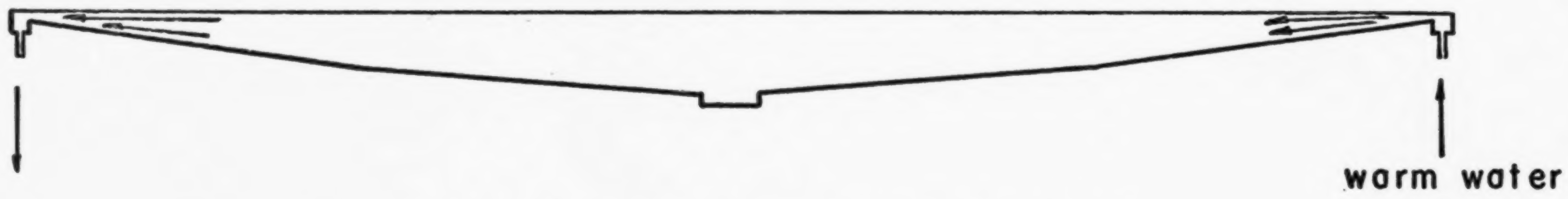
(This will result in some stratification. Warm surface layers may not be removed. Short circuiting of cold water.)



d.2 - Bottom Input of Warm Water, Surface Withdrawal

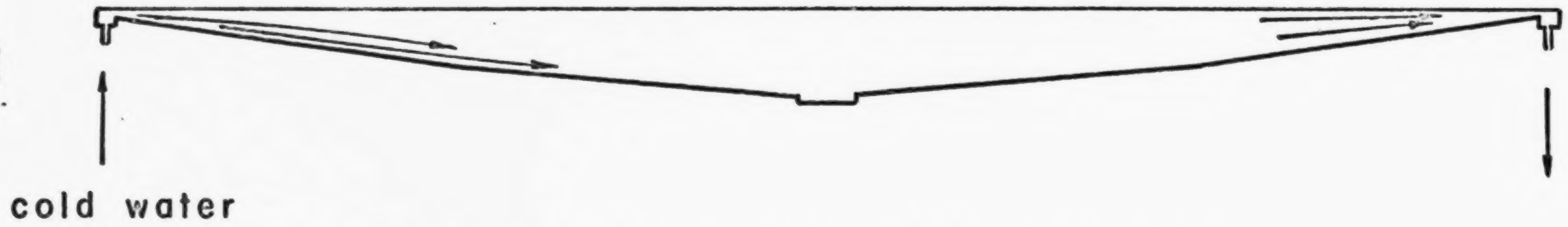
(Limited mixing, but thermal blanket. Natural convection will produce internal mixing.)

Fig. F-3 - Alternative Locations of Water Inlet and Outlet in a Pond



e.1 - Surface Inlet and Outlet in Shallow Portion of Pond

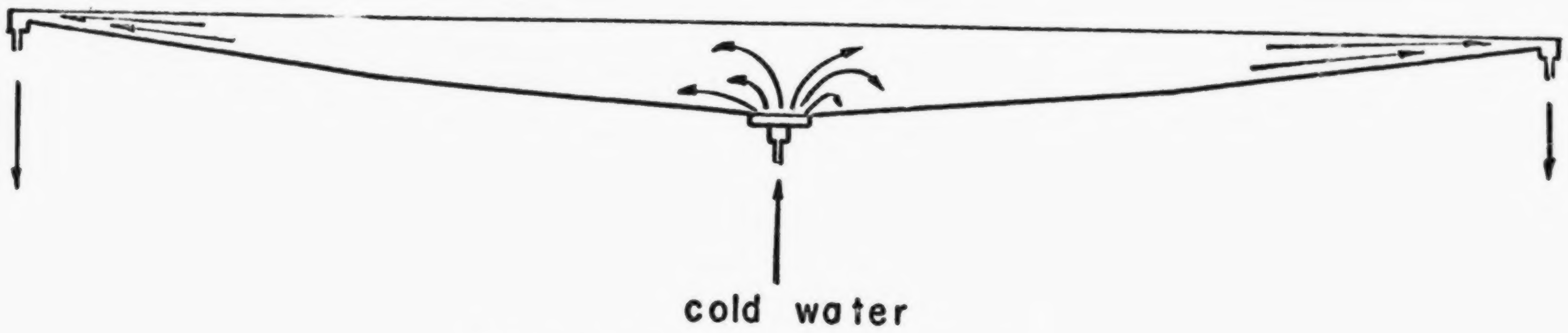
(Possible thermal blanket effect, but cold water not removed from bottom. Possible slow response due to great length.)



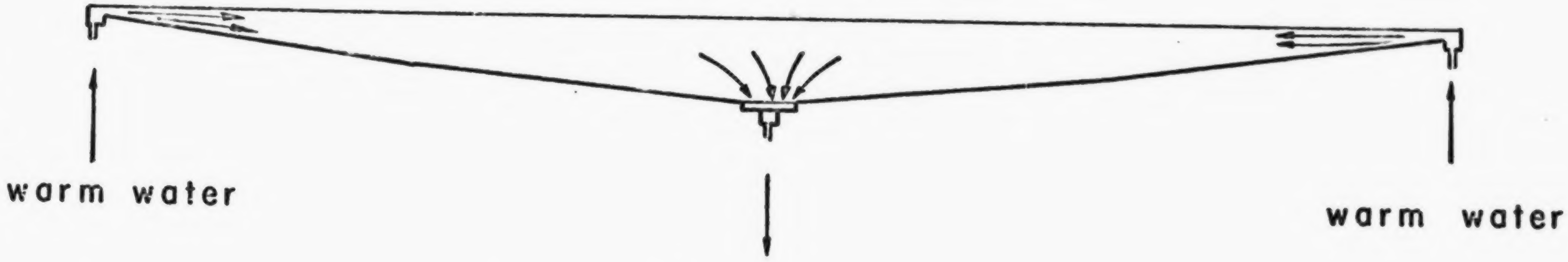
e.2 - Surface Inlet and Outlet in Shallow Portion of Pond

(Effective removal of warm water layer from surface, possibly slow response.)

Fig. F-3 - Alternative Locations of Water Inlet and Outlet in a Pond



f.1 - Bottom Inlet, Surface Withdrawal
(Effective removal of warm surface layer, little mixing, some stratification.)


warm water
warm water

f.2 - Surface Inlet, Bottom Withdrawal
(Effective heating, good response, vertical mixing by natural convection.)

Fig. F-3 - Alternative Locations of Water Inlet and Outlet in a Pond

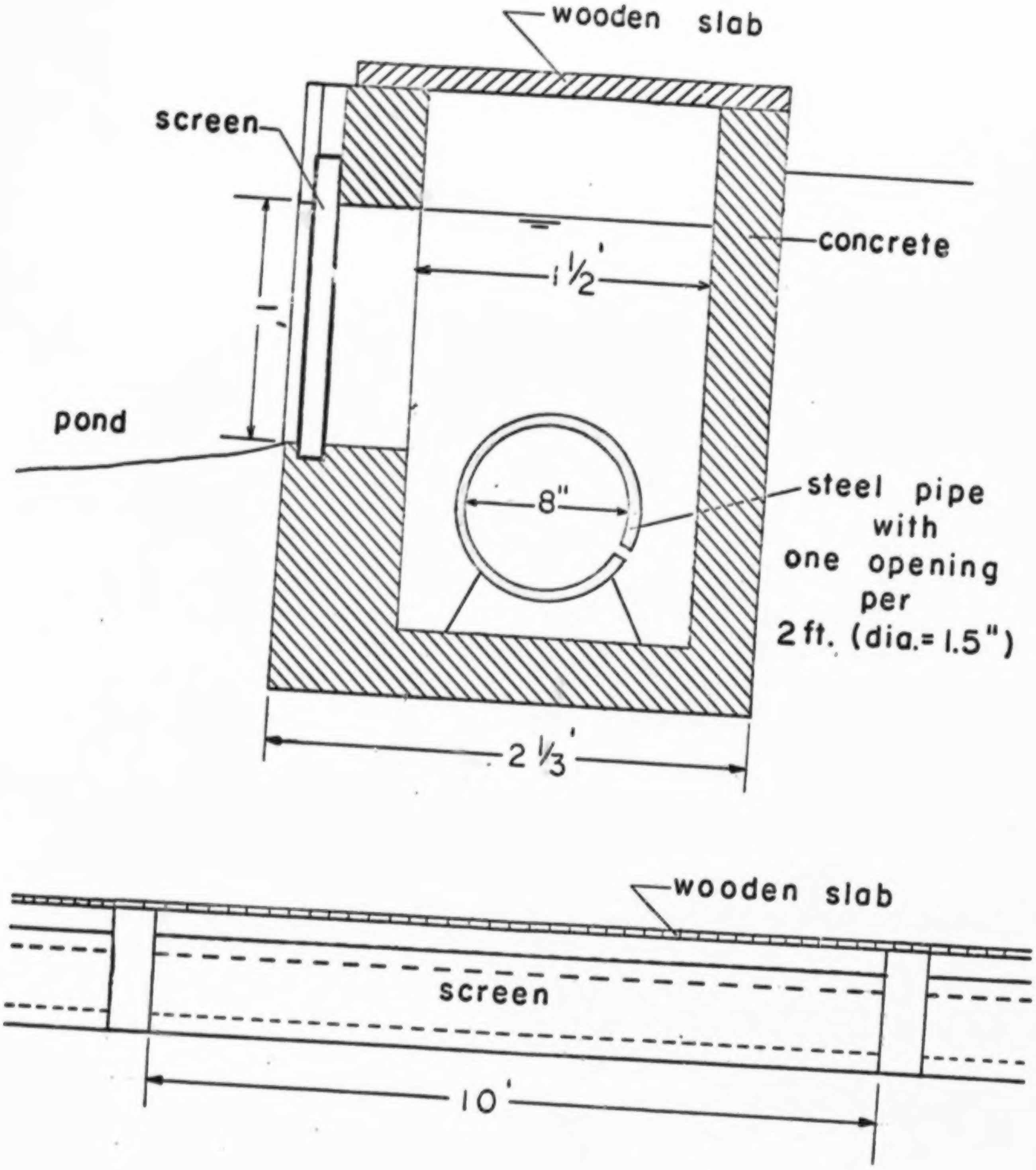

wooden slab
screen
concrete
1'
1 1/2'
pond
8"
steel pipe with one opening per 2 ft. (dia.= 1.5")
2 1/3'
wooden slab
screen
10'

Fig. F-4 - Schematic Arrangement of Peripheral Screens

G. SENSORS, CONTROLS, AND EMERGENCY OPERATION

Several important control parameters in the tempering water system for each pond can be identified. Two of these are primary controlled variables:

a. The prescribed operating water temperature of the pond

b. The prescribed pond water surface elevation

In principle, these two parameters are controlled quite simply, the temperature through addition or withdrawal of heat in the heat exchanger circulating system and the water level through addition of water. The two primary control systems will be closed loop regulators.

Due to restrictions imposed on the method by which heat and water can be added to the ponds, several secondary control parameters are involved. These are

a. The circulating water temperature change across the heat exchanger. Its value is limited to 6°F.

b. The circulating water flow rate. Its value may vary from zero to 2 cfs per pond, but the flow rate must be the same for each pond.

c. The heating or cooling water flow rate through each heat exchanger; this may vary between heat exchangers.

d. The make-up water flow rate. Its value must be the same for all ponds at any given time.

Sensors are needed for measuring the actual values of the controlled variables. The signals from these sensors will be transmitted to an error detector. The error between actual and prescribed values will serve as input to a controller. Automatic controls will be necessary, but manual control should also be possible.

1. Pond Temperature Control

Thermistors can be used as temperature sensors. Since complete uniformity of temperatures in a pond depends on several uncontrolled parameters, it seems advisable to use more than one sensor. The main temperature control sensors should be installed near the water surface, probably about one to two inches below the surface to assure fast response by the system. It may be necessary to use a float for support. The sensors should not be placed directly in front of either the water inlet or the outlet for the recirculation system, but rather midway between them. Temperature fluctuations are likely to be largest for the shallow portions of the pond, and one sensor should be installed there. The possibility of having at least one temperature sensor near the bottom of the pond should also be considered, particularly if both inlet and outlet are located near the surface. In this case replacement of the water near the bottom of the pond will be quite slow during the heating cycles, and some stratification may result. The flow patterns produced in the pond must be considered in selecting a location. In fact, the final decision on the location of the sensors can probably best be made after some test runs in the prototype.

The signal of each individual temperature sensor will be transmitted to a thermostat. One thermostat will be needed for each pond. An error--i.e., a difference between prescribed pond water temperature and actual water temperature--detected by the thermostat in any one of the ponds will activate all internal circulation pumps in all ponds, producing the same constant flow rate in all ponds. It is conceivable that in this process the error will be partially corrected due merely to the mixing of the pond water by pumping, and the pumping will then be stopped automatically.

The error signal from a given pond will also open the heat exchanger valves for that pond. These are normally closed. If the pond is too cool, both heating valves in Fig. F-1b will be opened. If the pond is too warm, both cooling valves will be opened. For those ponds in which there is no signal, all four valves will remain closed.

The actual amount of heating or cooling water circulated through a heat exchanger will be determined by control valves in the main lines as shown in Fig. F-1b. Normally these control valves will be wide open, producing little flow through the heat exchanger. However, at the same time as the error signal from the pond opens the heat exchanger valves in the pond circuit, it will also activate a thermostat measuring temperature change across the heat exchanger. This thermostat will partially close the appropriate control valve in the main line to produce the 6°F differential across the heat exchanger. This situation will be maintained as long as the pond thermostat carries a positive or negative signal. When that signal ceases, the main line control valve will open and the valves leading into and out of the heat exchanger will close. The control valve can be operated by oil-hydraulic or electric servo-mechanisms.

2. Water Level Control

This control can be manual or automatic. For an automatic system a water level sensor operating an on-off control valve would be used. Water level sensors and recorders of various makes are available. If all ponds are to receive equal quantities of make-up water, a single control valve will be installed in the make-up water supply line. However, there should be one sensor for each pond operating this single valve. An additional manually operated valve must be installed in each pond's make-up water line and adjusted to the desired flow before the ponds are put into operation.

With this system each pond would have an overflow weir and drain line which would prevent the water surface level from exceeding the predetermined level. The overflow weir can be installed at the end of the concrete channel, a cross section of which is shown in Fig. F-4. Make-up water should possibly be added in proximity to the weir. This water would either flow over the weir--if not needed in a specific pond--or be withdrawn through the intake pipe, mixed with pond water, and heated in the heat exchanger before it reached the interior of the pond.

3. Recorders

The actual values of several of the controlled variables should be recorded. These are

a. Water temperatures at several locations in the pond, including inlet and outlet.

b. Internal water circulation flow rate.

c. Make-up water flow rate.

Such records can be valuable in the selection of refined control procedures as well as in the interpretation of the experimental results obtained in the ponds. A constant record of pond water temperatures should, of course, be kept. The amount of heat added or withdrawn should also be recorded, as well as the amount of water which evaporates. To accomplish this, flow meters should be installed in both the internal water circulation system and the make-up water line.

4. Emergency Situations

A number of emergency situations could arise during the operation of the ponds caused by insufficient heating or cooling water supply, malfunction, or failure in the electrical or mechanical equipment. It is certainly impossible to foresee all possible emergencies, but some possibilities are readily anticipated and will be discussed in the following paragraphs. Warning buzzers and/or lights should be connected to the appropriate sensors to alert attendants when an abnormal situation arises.

4.1 Leakage of the Pond

Major leaks may be indicated by a failure of the make-up water supply to maintain a constant water level. It will be difficult to locate leaks without interfering with the experiments; therefore it is mandatory that the ponds be tested for some time before the experiments are started. If a major leak develops it can be traced using dye released in the water at the bottom of the pond. Repairs can be made under water using clay, fly-ash, or other sealing compounds, depending on the size of the opening.

4.2 Mechanical or Electrical Failure of the Recirculating Pump-Motor Unit

Under severe weather conditions such a failure must be repaired within six to twelve hours if major temperature changes in the pond are to be avoided. Since the ponds will be operated in pairs, it seems advisable to use one pump per pond and to provide a connection pipe with a manual valve between both suction and both discharge pipes so that one pump can pump water through both pipe systems under emergency conditions. In normal operation the valves in the connection lines would be closed. If one pump failed, the manually operated valves would be opened and the remaining pump would drive both systems.

In addition, manually operated valves must be installed on both ends of the pump so that a pump unit can be removed without interruption of the operation. One pump-motor unit should be in storage at all times.

4.3 Mechanical Failure of the Heat Exchanger

As under 4.2, two parallel heat exchangers with the possibility of interchange could be provided. This may be an unnecessary precaution, however, because the heat exchanger unit involves only stationary elements, and as a measure of economy it is not recommended. The valves at the entrance and exit of the heat exchanger are controlled and operated automatically. Manual operation of these valves should also be made possible, if necessary by installing a second non-automatic valve, so that the heat exchanger can be removed when necessary.

4.4 Failure of the Main Heating Water Supply Pump

Such a failure would result in the loss of the total heating capacity for all ponds. If the failure were not corrected within a 6- to 12-hour period, important temperature changes in the heated ponds might result if the meteorological conditions were unfavorable. The obvious solution is to have a standby unit available at all times. Another and probably less costly alternative is to accept a temperature drop to a lower level and to resume heating after repair or replacement of the unit. Running the pond temporarily on a natural temperature regime will be no problem in summer. However, in winter the ponds will freeze. To prevent a total freeze-out, well water at a temperature of approximately 50°F can be used. If well water is to be used for heating, automatic operation can be provided for with one additional thermostat control which will open the cooling water (well water) admission to the heat exchanger when the pond water temperature approaches, for example, 35°F. Manual control would probably be adequate, however, for the rare occasions when this operation would be necessary.

4.5 Failure of the Heating System

If the main heating source is not in operation, because of either planned maintenance or emergency conditions, an auxiliary heating source should be available. Since the auxiliary heating source might not be adequate to carry the full heating load, depending on meteorological conditions, some of the measures indicated in 4.4 above could be instituted. If the auxiliary heating system fails, insufficient heat or no heat will be available. The concepts described under 4.4 apply to this case as well.

4.6 Failure of Well Pump

Several wells, each equipped with its own pump, will have to be constructed. Simultaneous failure of all wells is quite unlikely unless there is a power outage. One pump unit should be in storage at all times.

4.7 Failure of Control Systems

A failure in the electronic control unit will result in either a lack or an excess of heating or cooling. Both situations can be discovered easily if the pond water temperatures at intake and outlet are recorded at all times, as is desirable for many reasons. If a malfunctioning of the electronic control system is observed, it must be possible to switch to manual control. Instructions for manual control should be posted and covered in great detail.

4.8 Simultaneous Failure of All Systems

A failure in the power supply system could produce a complete standstill. There might be adverse effects on both the pond water temperatures and the equipment. In summer the equipment would probably not suffer much, but in winter the water in the pipe systems would freeze after some time. It must therefore be possible to drain all pipes easily. A drain can be provided for the internal circulation system at the suction side of the pump. All pipes should have a slope such that water would flow to that drain due to gravity. The pipes in the external flow circuits should also have a slope toward the end of the main pipes from which the water will go to waste. Emergency pump units with internal combustion engines should be available to assist in drainage.

The effect on the pond itself would be very drastic in winter. Pond water temperatures would drop and an ice cover would eventually form. Before this occurred the pond water level should probably be dropped by approximately 1.5 ft so that the screens and the withdrawal trough would be dry before ice could form. All pipe systems should be drained except the one leading to the inlet in the pond.

If the thickness of the ice cover on the pond increased with time, the pond might freeze over its entire depth. The inlet pipe should also be drained before this happened.

It would probably be possible to restore normal operation after a complete breakdown of all systems, even during the winter. Well water would be needed for this operation. One would probably start by filling the main cooling water (well water) supply line. If the make-up water lines were then opened to maximum flow, well water of approximately 50°F would flow over the ice covering the pond and would drain over the overflow weirs. If this flow could be maintained without freezing, the ice cover would eventually melt or float to the surface of the pond. When this occurred the internal circulation system could be primed, the heat exchanger could be filled, and normal operation could be resumed. The total process would be highly dependent on meteorological conditions, however, because the water on top of the ice might itself freeze instead of removing the ice.

In any event it seems advisable to install a diesel-operated electric power generating unit to prevent a total failure of the system.

H. SUMMARY

It is recommended that the two warmest and the two coldest ponds be designed for the mean monthly temperatures specified in Appendix B-2, Set II. These mean temperatures can be maintained approximately 85 per cent of the time if an external heat input or withdrawal of the order of 4800 BTU ft^{-2} day^{-1} can be provided. During the remaining approximately 15 per cent of the time there may be uncontrollable temperature excursions beyond the limits set in Appendix B-2, Set II. The temperatures reached during periods of extreme weather are very likely to stay within $\pm 5^{\circ}$F of the prescribed temperatures. It should be possible to keep eight ponds ice-free in winter barring accidents involving the heating and circulating equipment. Maintaining the proposed temperatures will be easier if wind breaks are provided on the west-to-north quadrant of each pond in winter and on the east-to-south quadrant in summer. Two pairs of ponds with arbitrary intermediate temperature regimes can be operated within the same system.

It is impossible to produce completely uniform temperatures from the top to the bottom of a pond without violent mixing of the water. Since the experimental ponds are to represent fairly quiescent pools, some weak temperature stratification with depth must be accepted. The proposed circulating system has been designed to minimize these temperature differentials, but some mechanical mixing devices may be found necessary after the ponds are placed in operation in order to break up local stratification.

Heating water will be available at a flow rate of 2800 gpm from the Northern States Power plant at Monticello. The heating water temperature will follow the temperature pattern of the Mississippi River. The difference between river and heating water temperature will vary with the season, as described in part C. Occasionally, for periods of several hours or days, the heating water temperature may be too low to be useful. Such periods are likely to coincide with large heat demand to maintain pond water temperatures. It is therefore necessary that additional heat be available from an auxiliary heater to raise heating water temperatures to the required level. This heater may be identical with or part of the emergency heating system which will in any event be necessary, since the power plant will be shut down at regular intervals for maintenance and refueling. The auxiliary system should be capable of raising the heating water temperature by about 15°F.

Well water for cooling must be provided at a flow rate of 2 cfs if the coldest pond temperatures are to be maintained in summer at the levels outlined in Appendix B-2, Set II. This is a much larger flow rate than had been planned. Also, approximately 0.4 cfs of well water is needed as make-up water for eight ponds to compensate for evaporation and seepage losses. This flow can be withdrawn from the cooling water. Make-up water is to be added at the same rate to every pond. An overflow weir close to the input pipe will evacuate excess input from those ponds requiring less make-up water than is provided.

Both internal and external heat exchanger systems were examined. In general, both are feasible and adequate. An internal system consisting of parallel pipes laid just above the bottom of the ponds would be simpler and probably less expensive than an external system. However, several features of the internal system appear undesirable from a biological standpoint, and the NWQL has made a preliminary decision in favor of the external heat exchanger.

The external heating system will require recirculation of the pond water at a maximum rate of 2 cfs between each pond and its companion heat exchanger outside the pond. One heat exchanger can be used for each pair of ponds. Screened water intakes and outlets within the ponds and piping and pumps for recirculation are also required. A total of 180 sq ft of 40-mesh screen is recommended for each pond, 60 sq ft for the water inlet and 120 sq ft for the outlet. With these provisions, flow velocities through the screens will not exceed 0.1 fps. The larger area of the outlet screening takes account of trash accumulation.

Suggested piping arrangements for the external heat exchanger scheme are discussed in part F-3. Figure H-1 presents a schematic isometric view of a possible layout. The water inlet and outlet can be arranged in many different ways, and several possibilities have been sketched in Fig. F-3. The solution proposed in Fig. H-1 has several advantages over other possible arrangements, but it is not certain whether the mixing provided by the bottom inflow and the surface withdrawal will be sufficient to avoid stratification and "dead zones" in the ponds. Mechanical mixers whose locations will have to be determined from experience after the ponds are in operation may be necessary to disperse the water better. It is possible that a model study of the flow through one of the ponds would make it possible to locate the recirculating water inlets and outlets so that a minimum of mechanical mixing, or perhaps none at all, would be required. Several forms of reversible internal water circulation systems, as sketched in Fig. F-3, were considered. It is possible that flow reversal could somewhat increase the temperature uniformity in the ponds. However, for the sake of simpler flow control, the use of an irreversible system is proposed.

A sensing and control system is necessary to produce the desired pond water temperatures and to maintain constant water levels. The main elements of an automatic control system have been outlined in part G. With that system it should be possible to maintain temperatures in each pond within $\pm 2.5^{\circ}$F of the average nominal pond temperature 85 per cent of the time.

Several emergency situations, although certainly not all those possible, have been anticipated and are discussed in part F-4. It is recommended that an auxiliary heating system be installed in a bypass to the main heating water line and that a diesel-operated electric power generating unit be available to continue operation in case of a power failure. It may also be advisable to have a spare pump-motor unit for the internal circulation system and one for the well available at all times.

Finally, two general remarks seem in order. First, designing the proposed system for water temperature control in an outdoor experimental pond involved consideration of a great many parameters and phenomena. It was not possible to rely on well-established procedures. Basic information from such fields as hydrology, meteorology, fluid mechanics, and heat and mass transfer had to be combined to answer the many questions. Few unequivocal answers could be obtained. More often, severely limiting assumptions and simplifications were necessary to produce usable results. In some cases, such as in the locating of water intakes and outlets, solutions could only be suggested, because more precise answers would require three-dimensional physical model studies. This study has the character of a feasibility study. The best available knowledge was used, and the results presented can be assumed to reflect at least correct orders of magnitude.

The second point regards the availability of heating and cooling water at the selected Monticello site. Only heating water is readily available in sufficient quantity. Cooling water must be pumped from wells which will have to be built especially for that purpose. The temperature of the cooling water will be fairly constant and adequate, but that of the heating water will fluctuate up and down as the Mississippi River water temperature fluctuates. An auxiliary source of heat will therefore be necessary, as mentioned earlier. If a site were available near a power plant located on a deep lake, cooling water could probably be provided at less cost and less additional heat input would probably be required for the heating water.

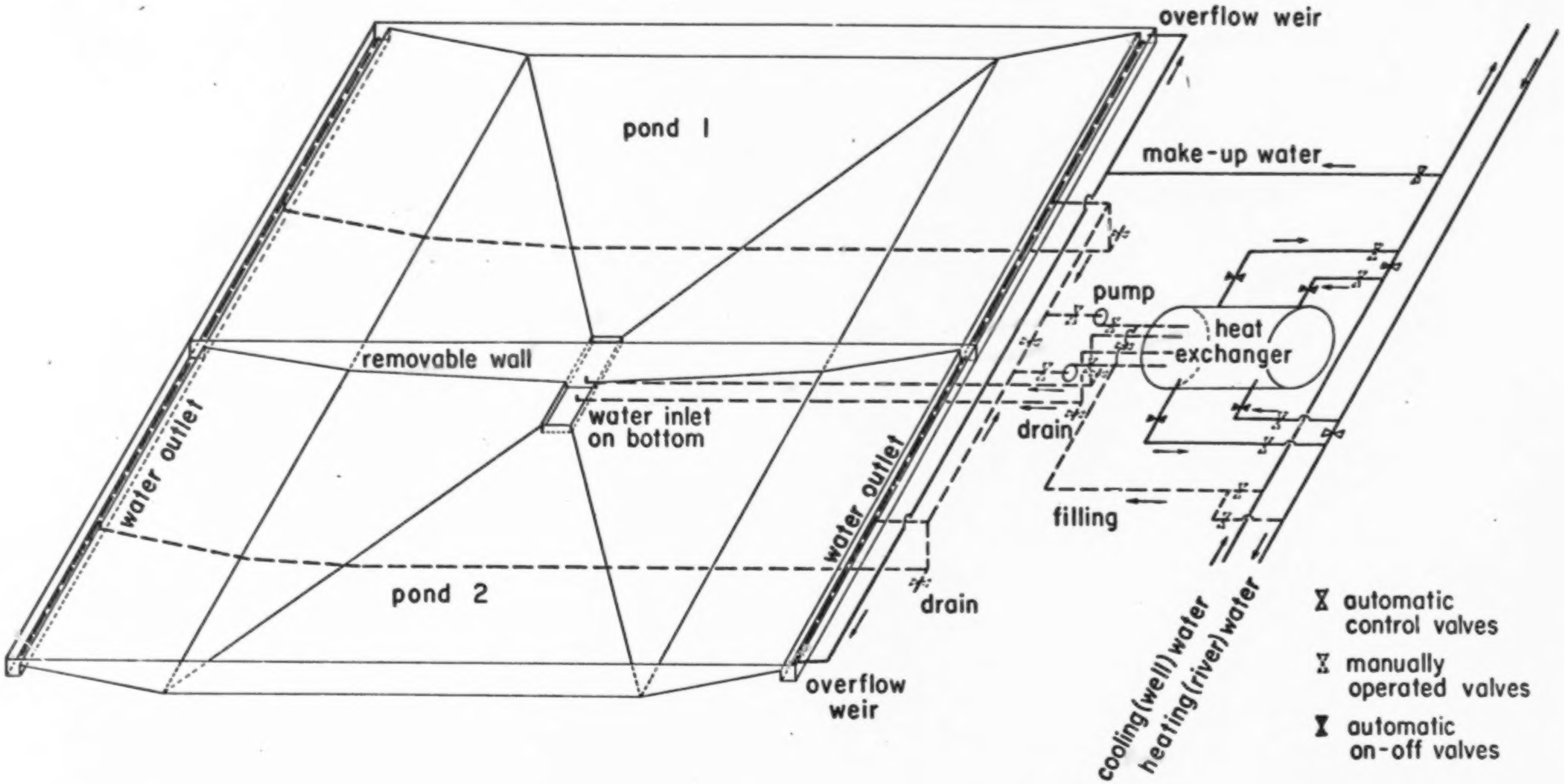

overflow weir
pond 1
make-up water
pump
heat exchanger
removable wall
water inlet on bottom
drain
water outlet
water outlet
filling
pond 2
drain
overflow weir
cooling (well) water
heating (river) water
automatic control valves
manually operated valves
automatic on-off valves

Fig. H-1 - Possible Arrangement of a Pair of Ponds at Same Temperature (There should be four such pairs operated at different temperatures.)

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APPENDIX A

CONTRIBUTIONS FROM THE HEAT TRANSFER LABORATORY

Mechanical Engineering Department, University of Minnesota

Professor E. R. G. Eckert, Director;
Professors R. Goldstein and E. Sparrow;
and Research Assistant R. Kolar

A-1 Heat Loss in Proposed Ponds, Preliminary
A-2 Time Response and Conduction Heating of Pond
A-3 Free Convection Heating of Proposed Monticello Ponds

APPENDIX A-1

Heat Loss in Proposed Ponds, Preliminary

A simple classical heat balance was applied to the surface of the proposed quarter acre ponds (maintained at 60°F) considering the heat transfer processes of back-radiation, convection-evaporation, and conduction. Solar input was calculated with some care and then averaged over the 24 hours of the day.

Specific calculations were made for the colder months when there will be a heat loss. For an average November day (t = 35°F, wind = 10 mph, humidity = 75 per cent), the average daily heat loss was calculated at 4435 BTU ft^{-2} day^{-1}. For an average January day (t = 6°F, wind = 10 mph, ϕ = 75 per cent) the figure is 7362 BTU ft^{-2} day^{-1}. An order-of-magnitude calculation for the time response to a temperature change is as follows: time constant = 0.026 $(hour)^{-1}$; the half-time response to a step temperature change is 26 hours.

The figures calculated are as yet only examples for use as planning guides. A report showing details of the calculation will soon be available.

APPENDIX A-2

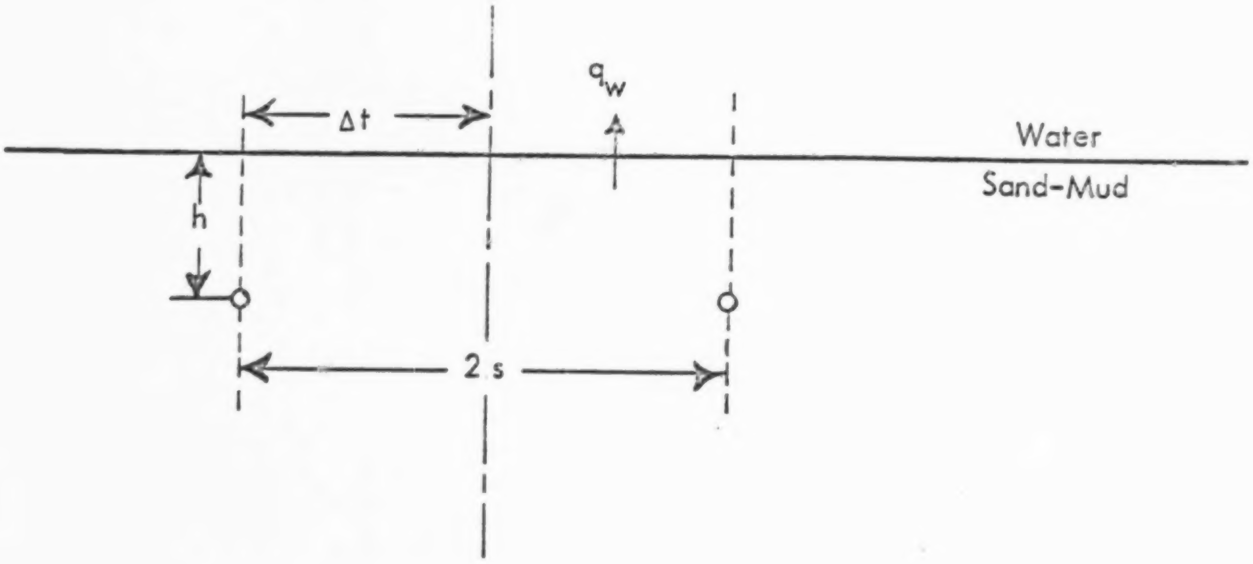
Time Response and Conduction Heating of Pond

Calculations at the Heat Transfer Laboratory during the last reporting period have been concerned with the problem of how to arrange tubes for the heating of the pond during the winter months in such a way as to minimize local temperature variations along the bottom of the pond.

Previous calculations had established surface heat fluxes of 4300 and 7400 BTU ft^{-2} day^{-1} for average days in November and January, respectively. The time response of the pond to temperature fluctuations in the atmosphere had been characterized by its "half value time," defined as the time which is required to decrease an instantaneously established initial temperature difference to half the original value. A value of 26 hours had been obtained for representative conditions. This magnitude of the half value time was used to determine to what degree the daily temperature fluctuations in the atmosphere are damped in the water body. It was found that the temperature fluctuation in the water body is approximately one-tenth of the daily fluctuation in the atmosphere. All these calculations are based on the assumption that no local temperature differences exist in the water body.

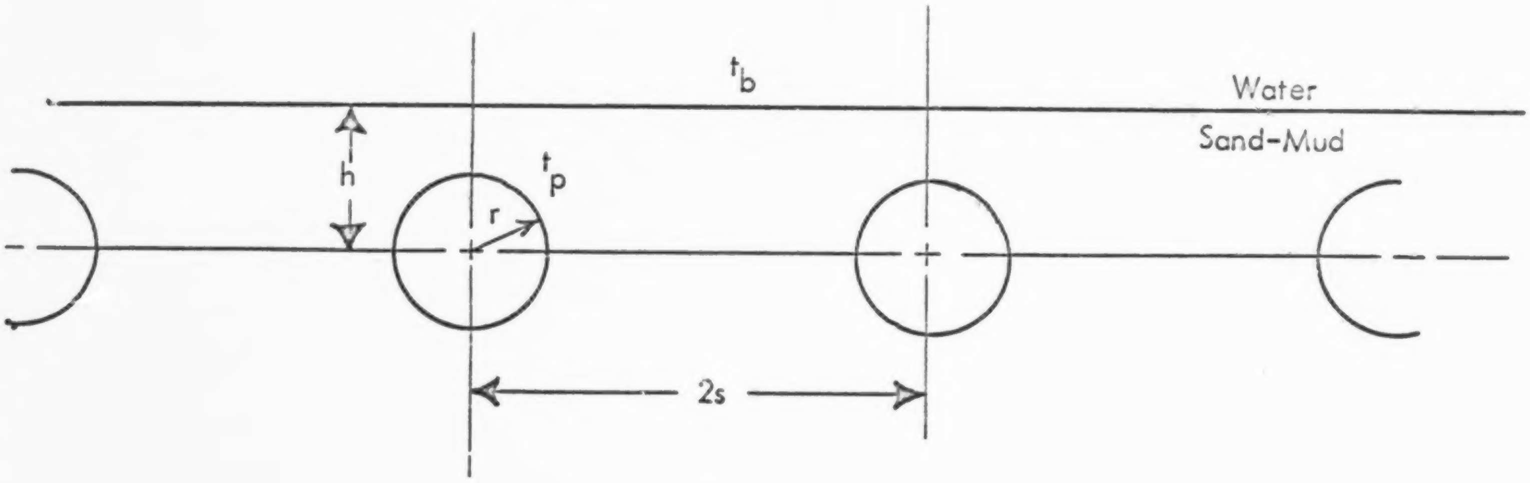
Calculations of the half value time were extended during the last period to investigate different combinations of wind speeds and relative humidity. The results are presented in the attached Figs. 1 and 2. It can be seen that the half value time is a strong function of wind speed while hardly affected by humidity variations.

Another analysis was performed to predict the local temperature variations along the bottom of the pond when heating of the water is performed by pipes buried in the sand at some depth below the pond floor. The calculation was made in two steps. In the first step the tubes were replaced by line heat sources according to Sketch a, with q_w indicating the heat flux per unit surface area through the bottom of the pond and Δt indicating the maximum temperature difference along the bottom of the pond. A computer solution by Mr. H. Miyazaki resulted in a relation of the parameter $\Delta t/(q_w h/k)$ as a function of the length ratio s/h. The symbol k denotes the thermal conductivity of the sand. For the calculation, the heat flux q_w was specified as constant along the bottom of the pond, and this resulted in a temperature difference Δt somewhat larger than that actually encountered at the bottom of the pond. No distinction was made between the thermal conductivity of the sand in which the tubes were embedded and that of a layer of mud on top of the sand. Both were assumed to be saturated with water.



SKETCH a

The second step in the calculation is intended to introduce the fact that the pipes have a finite radius. It was based on solutions contained in the book, Heat Transfer, by Kutateladze, in which relations are presented which determine the difference between the surface temperature t_p of the pipes and the temperature t_b of the bottom of the pond based on the assumption that the last-mentioned temperature is locally uniform. Sketch b presents the geometry involved. It was argued that this solution could



SKETCH b

still be accepted as a good approximation as long as the temperature variation Δt was small compared to the difference $t_p - t_b$. The solution in the above-mentioned book can be brought into the form $q_w 2sL = \frac{1}{R*} (t_p - t_s)$ with L indicating the length of the tubes and R* denoting a heat conduction resistance. Values for this resistance are contained in the referenced book. Combining this relation with one obtained by the computer solution, one can express the parameter $\eta = \frac{\Delta t}{t_p - t_b}$ as a function of the two geometric ratios s/h and r/s with r indicating the pipe radius. Figure 3 presents the results of this analysis. They can be considered good approximations of the actual situation in the range in which the value of η is small compared to one. For preliminary design considerations, the figure can probably be used up to values of $\eta = 0.2$.

With this information available, it is now planned to consider the actual design of the heating system.

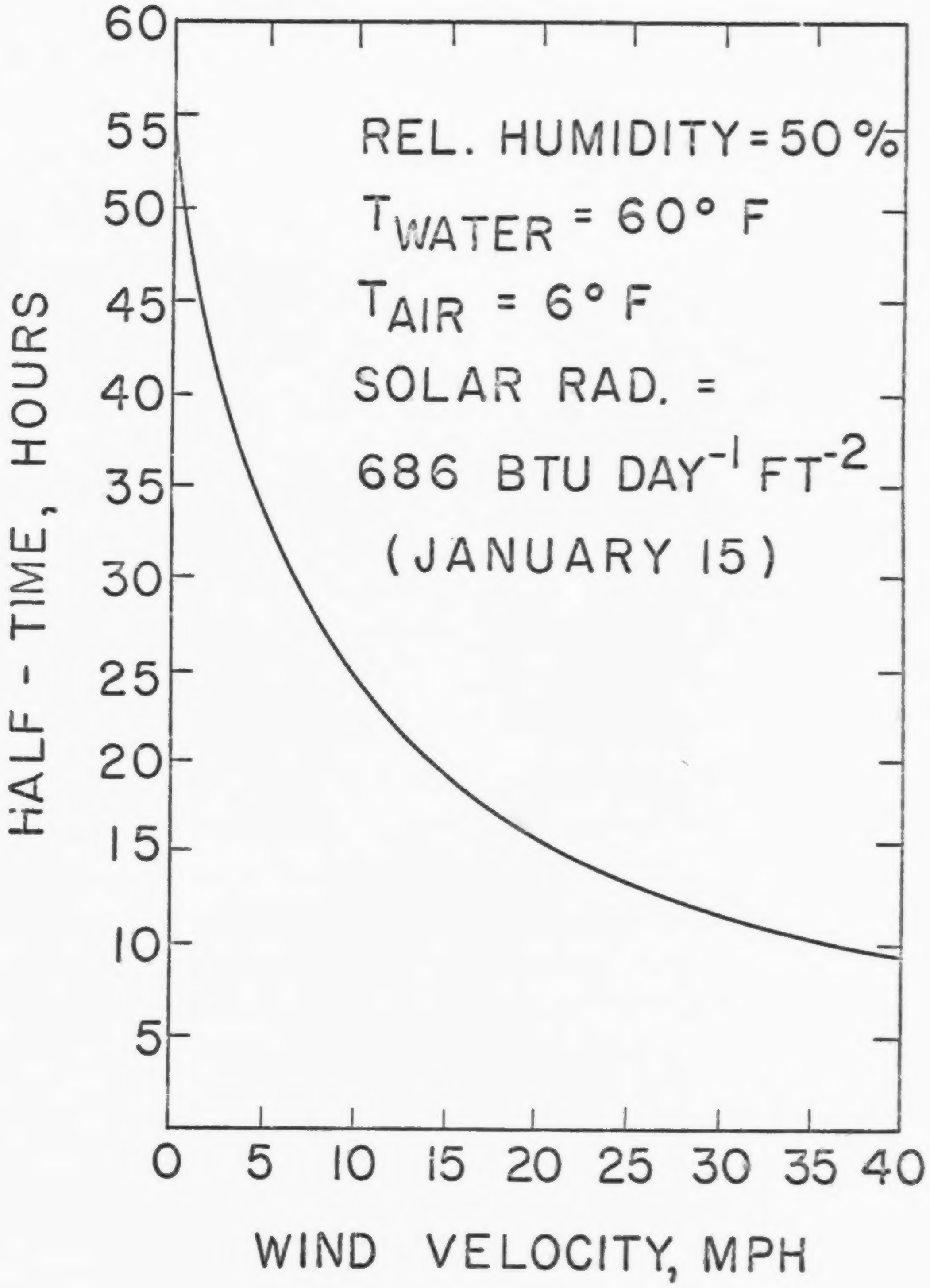


Fig. 1 (Appendix A-2)

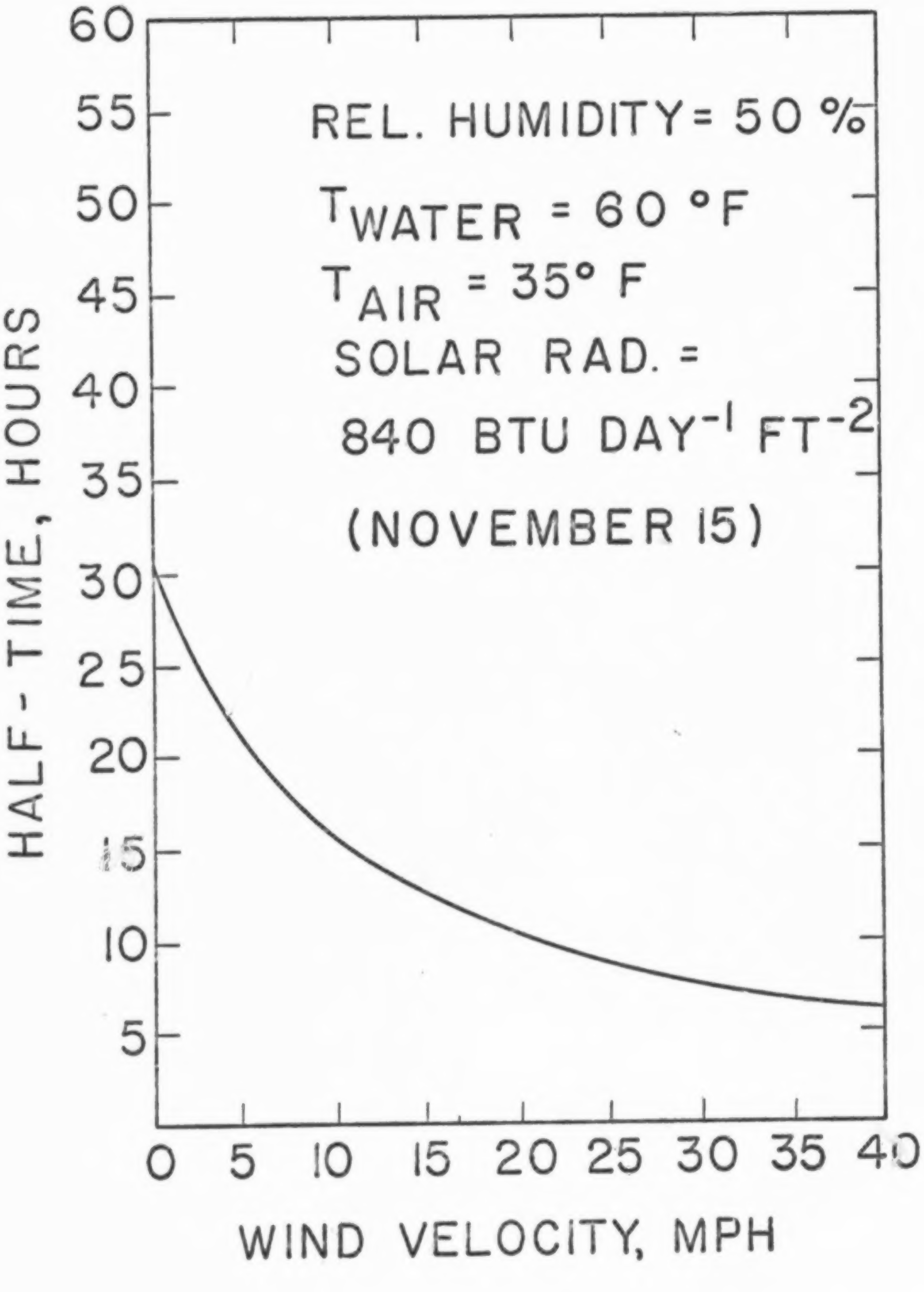


Fig. 2(a) (Appendix A-2)

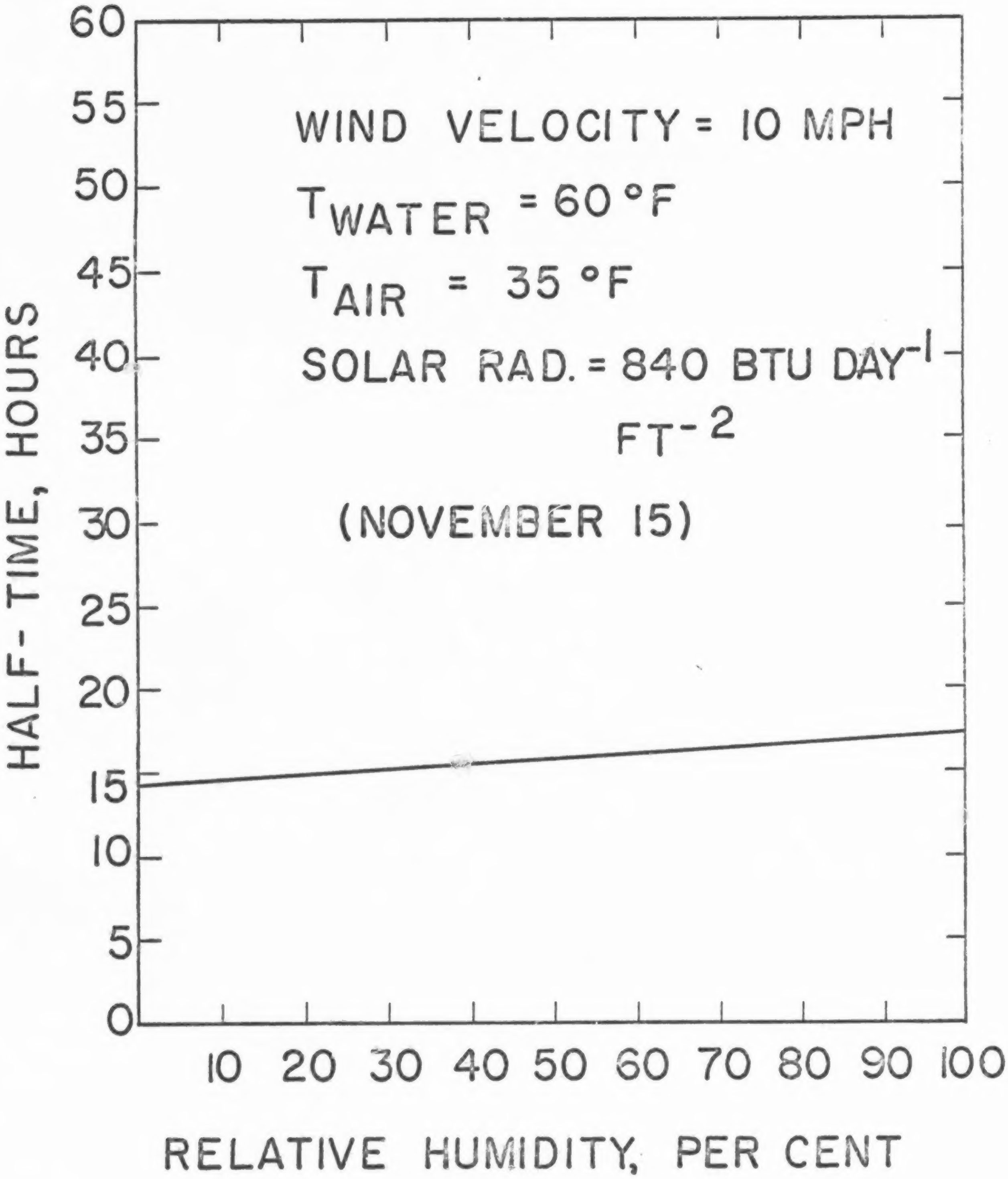


Fig. 2(b) (Appendix A-2)

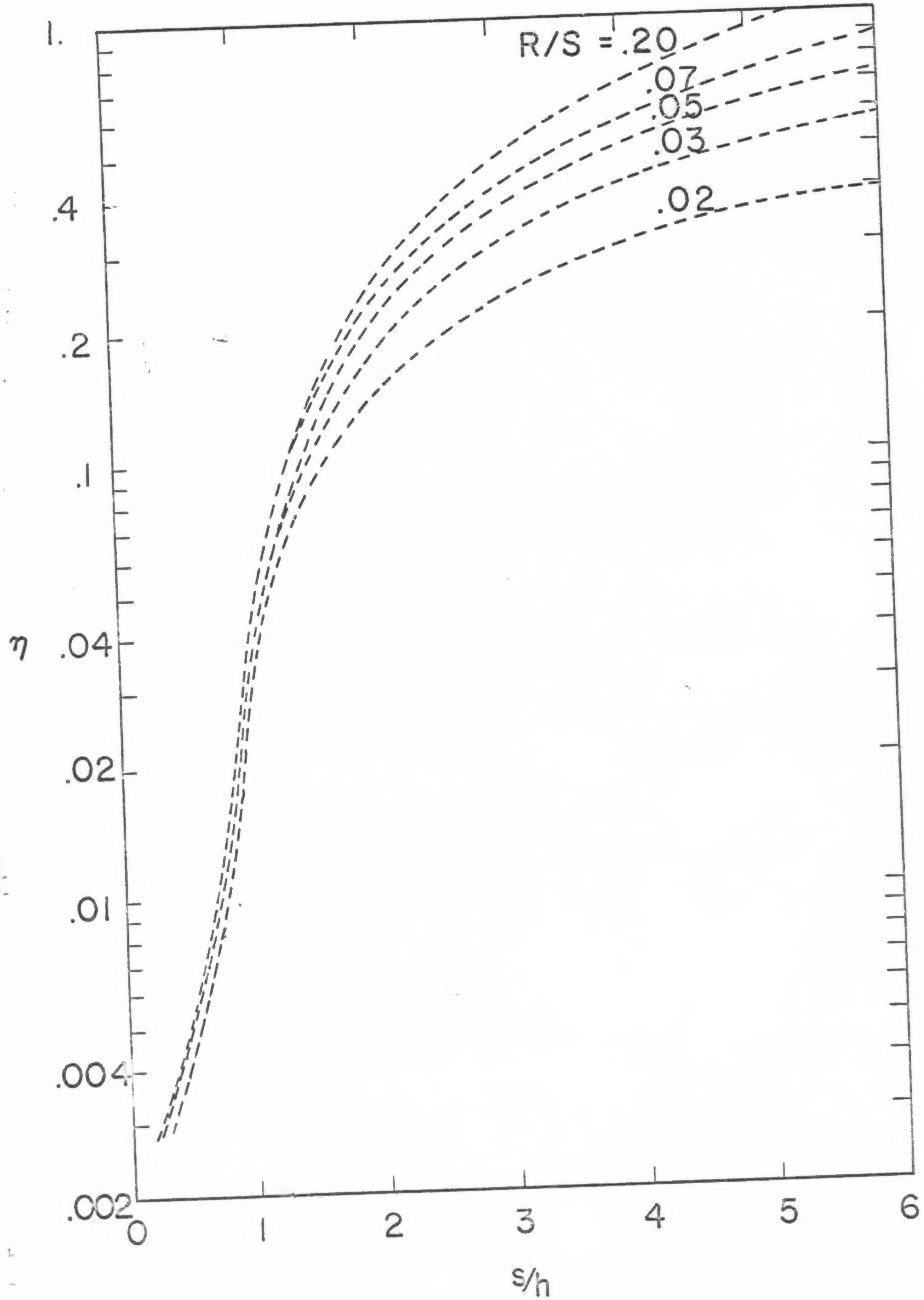


Fig. 3 (Appendix A-2)

APPENDIX A-3

Free Convection Heating of Proposed Monticello Ponds

Calculations under the original proposal for burying the heating tubes in the mud indicated that temperature differences arise in the sand and mud layer which cannot be tolerated. The response of the temperature in the pond to a change in heating condition would also be extremely slow. For this reason a new arrangement has been investigated in which the heating tubes are placed on top of the bottom of the pond and transfer the heat directly to the pond water. A temperature difference is then required to transfer the heat from the surface of the pipes to the water by natural convection. A calculation gives the following typical results:

For representative conditions in January, the severest month, surface heat fluxes average 9216 BTU ft^{-2} day^{-1}. If we consider 2-inch-diameter pipes spaced across the lower depths such that 1/10 of the pond bottom area is covered by pipes, about a 21.5°F temperature difference is necessary between the pipe surface and the pond bulk temperature. For 2/10 of the bottom covered, the figure is 11.5°F, while for 3/10 an 8.5°F temperature difference is necessary. If we go still further to 5/10 or 1/2 of the bottom covered by pipes, only a 5.5°F temperature difference is needed, while 7/10 yields a figure of 4°F. These results are probably somewhat conservative because the turbulence which is created in the pond by these temperature differences will tend to reduce the differences, and this effect has not been included in the calculation.

The heat supplied from the pipes to the water in the pond has to be transferred from the bulk of the pond water to the atmosphere. This generates an additional temperature drop near the water surface of the order of 3° to 4°F.

The temperature differences mentioned above may be considered too large for the purpose for which the pond is to be built. They can be reduced if a reduction in the surface heat flux is accepted. The temperature differences are approximately proportional to this heat flux. A reduction of the surface heat flux to 4108 BTU ft^{-2} day^{-1} thus reduces all temperature differences to half the values listed above.

For the heat flux condition of 9216 BTU ft^{-2} day^{-1} the temperature of the heating water has to be at least 20°F above the temperature in the bulk of the pond. For a temperature of 60°F in the pond, therefore, the heating water has to be available at a temperature of 80°F. A reduction in the heat flux will also make it possible to operate with a smaller heating water temperature.

Table 1 (Appendix A-3)

$\Delta T = 3^{o}R$

Pipe Diameter (Inches)	FREE CONVECTION			FORCED CONVECTION 20 mph Wind ⇒ 0.586 ft/sec Water
	Ra No.	Nu_o*	Nu_o**	Nu_o***
1	2.64×10^5	11.226 (h = 46.206)	12.018	64.282
2	2.11×10^6	18.592 (h = 38.26)	20.211	98.426
3	7.13×10^6	25.148 (h = 34.50)	27.394	126.332
4	1.69×10^7	31.228 (h = 32.13)	33.991	150.829
5	3.30×10^7	36.98 (h = 30.44)	40.184	173.068
6	5.71×10^7	42.48 (h = 29.14)	46.072	193.658
7	9.06×10^7	47.78 (h = 28.09)	51.718	212.971
8	1.35×10^8	52.92 (h = 27.24)	57.166	231.255

$$*Nu_o = \frac{2}{\ln[1 + \frac{5.01}{Ra^{.26}}]}$$

$$**Nu_o = 0.53(Ra)^{1/4}$$

$$***Nu_o = 0.43 + 0.19314(Re_j)^{.613}\ Pr^{.31} \quad \text{for} \quad 4000 \leq Re_j \leq 40{,}000$$

Table 2 (Appendix A-3)

$\Delta T = 5^{o}R$

Pipe Diameter (Inches)	FREE CONVECTION			FORCED CONVECTION 20 mph Wind ⇒ 0.586 ft/sec Water
	Ra No.	Nu_o*	Nu_o**	Nu_o***
1	4.40×10^5	12.686 (h = 52.22)	13.655	64.282
2	3.52×10^6	21.096 (h = 43.41)	22.964	98.426
3	1.19×10^7	28.581 (h = 39.21)	31.126	126.332
4	2.82×10^7	35.525 (h = 36.55)	38.622	150.829
5	5.51×10^7	42.092 (h = 34.65)	45.657	173.068
6	9.52×10^7	48.374 (h = 33.18)	52.348	193.658
7	1.51×10^8	54.428 (h = 32)	58.763	212.971
8	2.26×10^8	60.294 (h = 31.02)	64.953	231.255

$$*Nu_o = \frac{2}{\ln[1 + \frac{5.01}{Ra^{.26}}]}$$

$$**Nu_o = 0.53(Ra)^{1/4}$$

$$***Nu_o = 0.43 + 0.19314(Re_j)^{.613}\, Pr^{.31} \quad \text{for} \quad 4000 \leq Re_j \leq 40{,}000$$

Table 3 (Appendix A-3)

$\Delta T = 7^{o}R$

Pipe Diameter (Inches)	FREE CONVECTION			FORCED CONVECTION 20 mph Wind ⇒ 0.586 ft/sec Water
	Ra No.	Nu_o*	Nu_o**	Nu_o***
1	6.17×10^5	13.759 (h = 56.63)	14.853	64.282
2	4.93×10^6	22.936 (h = 47.20)	24.980	98.426
3	1.66×10^7	31.105 (h = 42.68)	33.858	126.332
4	3.95×10^7	38.683 (h = 39.80)	42.011	150.829
5	7.71×10^7	45.849 (h = 37.74)	49.664	173.068
6	1.33×10^8	52.706 (h = 36.16)	56.942	193.658
7	2.12×10^8	59.313 (h = 34.88)	63.920	212.971
8	3.16×10^8	65.716 (h = 33.81)	70.653	231.255

$$*Nu_o = \frac{2}{\ln[1 + \frac{5.01}{Ra^{.26}}]}$$

$$**Nu_o = 0.53(Ra)^{1/4}$$

$$***Nu_o = 0.43 + 0.19314(Re_j)^{.613}\ Pr^{.31} \quad \text{for} \quad 4000 \leqslant Re_j \leqslant 40{,}000$$

Table 4 (Appendix A-3)

$\Delta T = 10^{\circ}R$

Pipe Diameter (Inches)	FREE CONVECTION			FORCED CONVECTION 20 mph Wind ⇒ 0.586 ft/sec Water
	Ra No.	Nu_o*	Nu_o**	Nu_o***
1	8.81×10^5	15.003		64.282
2	7.05×10^6	25.070 (h = 51.59)		98.426
3	2.38×10^7	34.03 (h = 46.691)		126.332
4	5.64×10^7	42.34 (h = 43.57)		150.829
5	1.10×10^8	50.21 (h = 41.33)		173.068
6	1.90×10^8	57.73 (h = 39.6)		193.658
7	3.02×10^8	64.98 (h = 38.21)		212.971
8	4.51×10^8	72.00 (h = 37.05)		231.255

$$*Nu_o = \frac{2}{\ln[1 + \frac{5.01}{Ra^{.26}}]}$$

$$**Nu_o = 0.53(Ra)^{1/4}$$

$$***Nu_o = 0.43 + 0.19314(Re_j)^{.613}\ Pr^{.31} \quad \text{for} \quad 4000 \leq Re_j \leq 40,000$$

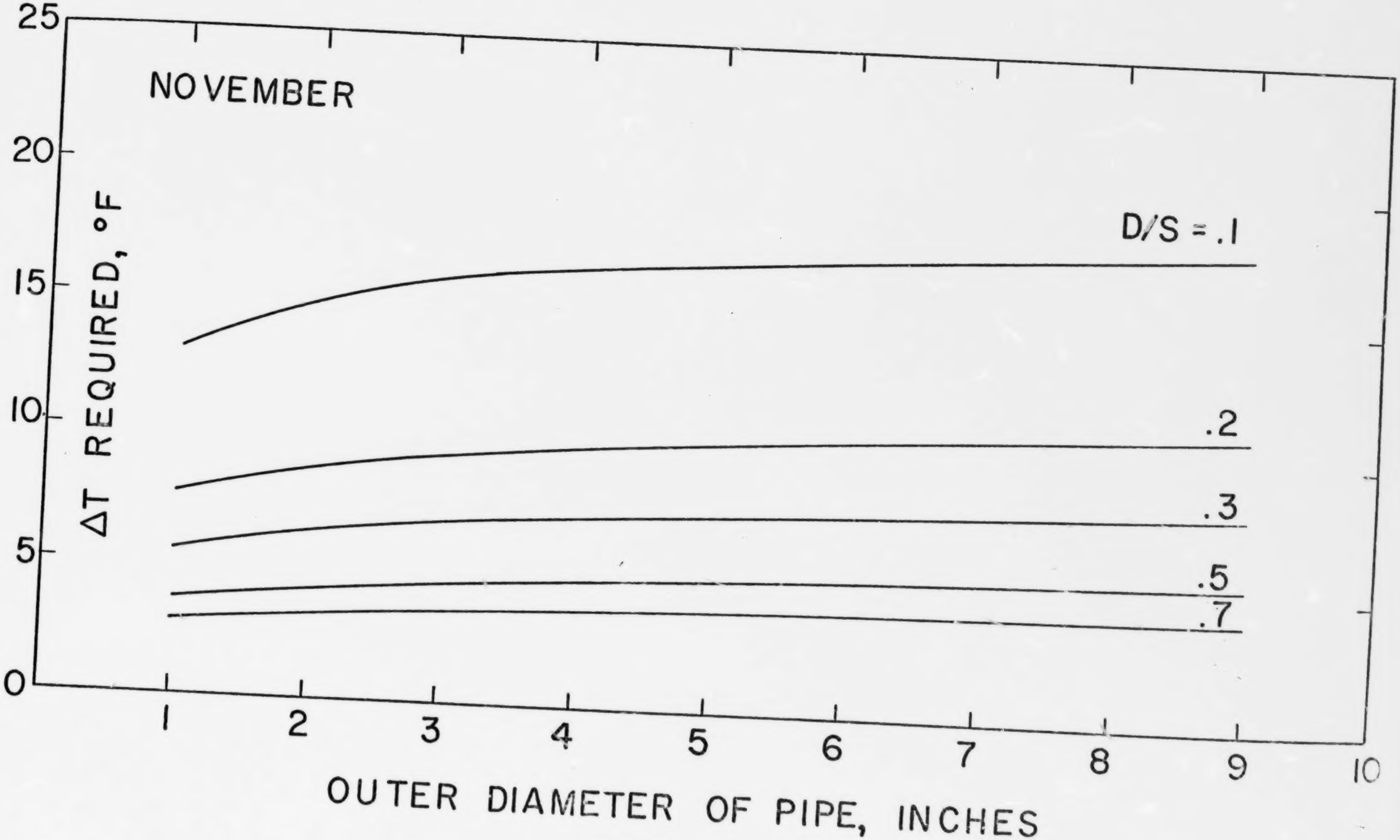


Fig. 1 (Appendix A-3)

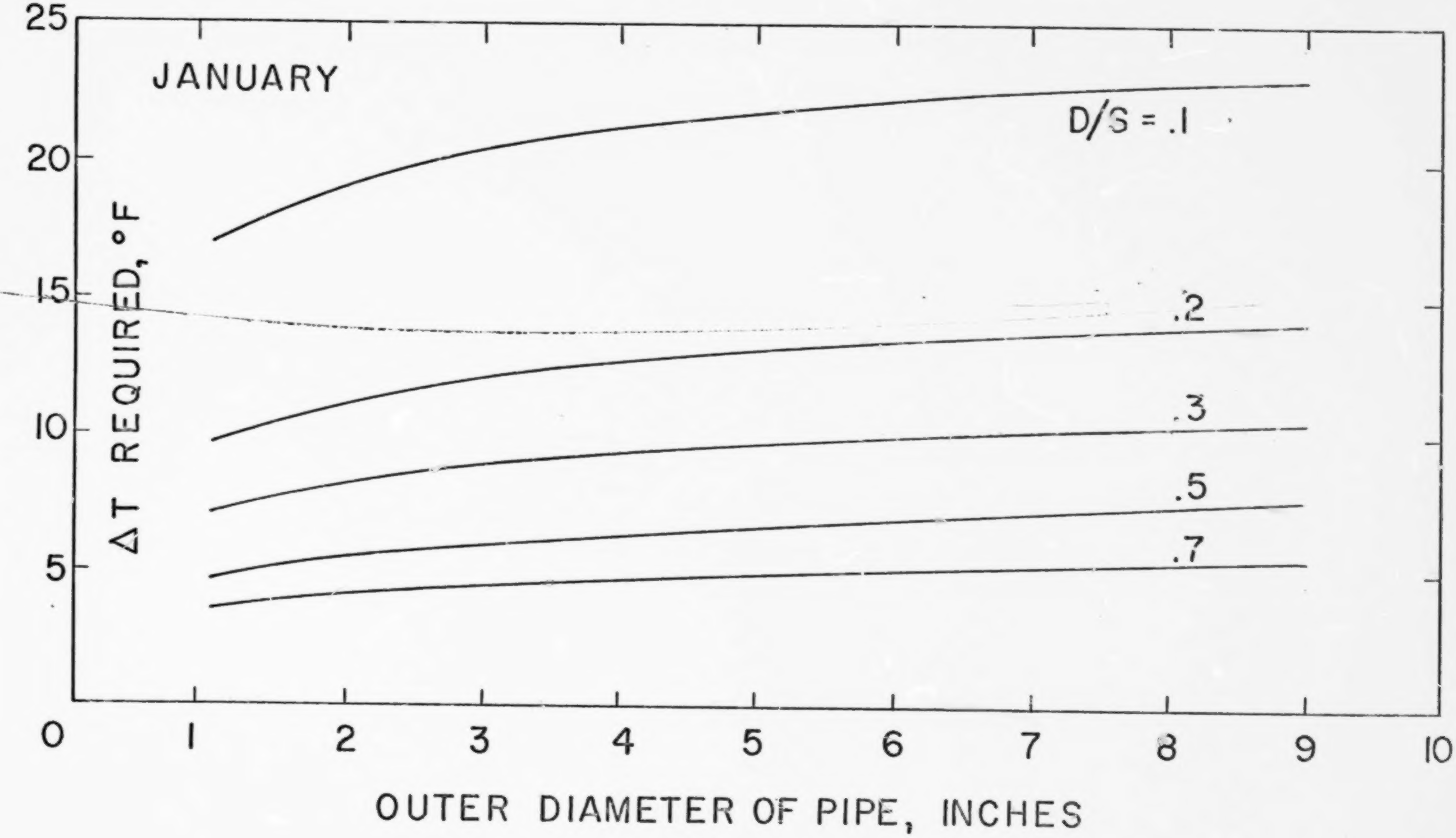


Fig. 2 (Appendix A-3)

Appendix B-1

MEAN MONTHLY METEOROLOGICAL CONDITIONS

Month	Solar Rad. H_s (Langleys) (1)	Air Temp. T_a (^oF) (2)	Wind Speed U (mph) (3)	Vapor Pressure e_a (in Hg) (4)	Total Precipitation (in.) (5)
Jan	174	10.1	10.7	.074	0.72
Feb	269	13.4	11.0	.082	0.80
Mar	357	25.6	11.3	.125	1.28
Apr	429	42.8	12.3	.197	2.02
May	493	55.6	11.2	.301	3.51
June	539	65.2	10.7	.456	4.49
July	564	71.0	9.2	.523	3.26
Aug	499	68.6	9.4	.486	3.73
Sept	340	58.8	10.2	.386	2.41
Oct	241	47.3	11.0	.246	1.64
Nov	147	29.5	11.2	.146	1.33
Dec	122	16.6	10.8	.094	0.73

Appendix B-2

ESTIMATED MEAN MONTHLY POND TEMPERATURES IN ^{o}F

SET I

Month	Hottest	Coldest
Jan	56	32 (Heated)
Feb	56	32 (Heated)
Mar	58	35 (Natural)
Apr	57	44 (Natural)
May	72	59 (Natural)
June	81	62 (Cooled)
July	89	62 (Cooled)
Aug	86	62 (Cooled)
Sept	78	62 (Cooled)
Oct	75	52 (Natural)
Nov	63	40 (Natural)
Dec	57	34 (Natural)

SET II

Month	Hottest	Coldest
Jan	47	32
Feb	51	32
Mar	58	37
Apr	57	46
May	72	60
June	81	64
July	89	67
Aug	86	64
Sept	76	62
Oct	68	55
Nov	54	43
Dec	49	37

Appendix B-3

COMPARISON OF MONTHLY MEANS AND EXTREMES OF NET SURFACE HEAT FLUX (INCLUDING PRECIPITATION) FOR HOTTEST AND COLDEST POND in BTU ft^{-2} day^{-1}

POND TEMPERATURES OF APPENDIX B-2, Set I

	Hottest Pond			Coldest Pond		
Month	Mean	Low*	Ratio	Mean	High**	Ratio
Jan	-3723	-5600	1.5	-1128	+1500	
Feb	-3189	-5900	1.8	-565	+2300	
Mar	-2267	-4800	2.1	+374	+3300	8.8
Apr	-524	-3000	5.7	+1115	+4300	3.9
May	-1256	-4300	3.4	+780	+4100	5.3
June	-1478	-4100	2.7	+1798	+4700	2.6
July	-2207	-4800	2.2	+2530	+5700	2.3
Aug	-2118	-4500	2.1	+2002	+4900	2.4
Sept	-2235	-5200	2.2	+385	+3400	8.8
Oct	-3455	-5800	1.7	+12	+2800	
Nov	-3410	-6300	1.8	-568	+2400	
Dec	-3590	-5800	1.6	-1038	+1200	

*Approx. 85 per cent probability of exceedence

**Approx. 15 per cent probability of exceedence

POND TEMPERATURES OF APPENDIX B-2, Set II

	Hottest Pond			Coldest Pond		
Month	Mean	Low*	Ratio	Mean	High**	Ratio
Jan	-2640	-4110	1.5	-1128	+970	--
Feb	-2560	-4440	1.7	-565	+1840	--
Mar	-2267	-4700	2.1	178	+2340	13.1
Apr	-524	-3000	5.7	884	+3780	4.3
May	-1256	-4300	3.4	641	+3610	5.6
June	-1478	-4100	2.8	1504	+4220	2.8
July	-2207	-4800	2.2	1819	+4720	2.6
Aug	-2118	-4500	2.1	1723	+4440	2.6
Sept	-1863	-4170	2.2	385	+2900	7.5
Oct	-2246	-3830	1.7	-367	+2340	--
Nov	-2169	-4310	2.0	-881	+1420	--
Dec	-2598	-4330	1.7	-1325	+660	--

*Approx. 85 per cent probability of exceedence

**Approx. 15 per cent probability of exceedence

MEAN MONTHLY WATER BUDGET OF HOTTEST POND
IN INCHES OF WATER PER DAY

Month	Precipitation	Calculated Evaporation	Estimated Seepage	Total Water Increment
Jan	+0.02	-1.96	-0.5	-2.4
Feb	+0.03	-1.94	-0.5	-2.4
Mar	+0.04	-1.92	-0.5	-2.4
Apr	+0.06	-1.52	-0.5	-2.0
May	+0.11	-2.60	-0.5	-3.0
June	+0.15	-3.17	-0.5	-3.5
July	+0.11	-4.11	-0.5	-4.5
Aug	+0.12	-3.73	-0.5	-4.1
Sept	+0.08	-2.94	-0.5	-3.4
Oct	+0.05	-3.31	-0.5	-3.8
Nov	+0.04	-2.30	-0.5	-2.8
Dec	+0.02	-1.95	-0.5	-2.4